BENEFITS ASSESSMENT OF REDUCED SEPARATIONS IN NORTH ATLANTIC ORGANIZED TRACK SYSTEM

Prepared by:

Almira R. Williams

CSSI Inc., Advanced Programs

400 Virginia Ave. SW

Washington, DC

Prepared for:

NASA Glenn Research Center

CLEVELAND, OH

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1 Introduction

The recent doubling in fuel prices[1] have had a significant impact on all air-carrier operations; however, due to their larger take-off weights and longer durations, trans-oceanic flights have been affected more than domestic flights. Though only constituting 4 percent of total U.S. air carrier operations, oceanic flights consume 26 percent of all fuel. On the other hand, oceanic flights generate 49% of all cargo revenue and 20% of all passenger revenue. In fact, these flights are known to generate sufficient revenue to support service on some domestic markets that otherwise would not be sustainable. Therefore, the profitability of international flights is critical in supporting the domestic hubs from which they originate.

As a result, air carriers are very interested in finding new ways to improve operational efficiency within the Oceanic environment. The recent implementation of Advanced Technologies in Oceanic Procedures (ATOP) in the Oakland and New York oceanic regions and the corresponding potential to significantly reduce separations in those regions has raised the obvious question of extending the benefits to the adjacent oceanic regions. One of the most congested and, therefore, potentially most fruitful areas for such improvements, is the North Atlantic Organized Track System (NAT OTS).

This report summarizes an investigation of benefits enabled by reducing the horizontal separations between appropriately equipped oceanic flights on NAT OTS. This research effort did not address the issue of minimum equipage requirements; it was assumed that the equipped flights were capable of maintaining situational awareness and navigation accuracy necessary to support safe operations with the separation standards of 30 NM longitudinally and 0.5 degrees laterally. These reduced separations are applicable only between two equipped flights.

The main focus of this research was the sensitivity of benefits to demand and equipage levels, and the effect of procedural rules including the following three cases: (1) mixed operations of the non-equipped and equipped flights throughout the track system, (2) operations of the non-equipped flights prohibited on reduced-separations tracks (further referred to as segregated tracks), and (3) lateral separations between two adjacent segregated tracks reduced to allow for placing an additional track available only to the equipped flights. Three levels of demand were investigated: traffic demand forecasted for 2005, 2010, and 2015. Traffic forecasts were generated using actual flight schedules realized in 2004 as baseline, and traffic growth parameters published by the ICAO North Atlantic Office. For each of the demand levels, five levels of equipage were investigated: 0, 25, 50, 75 and 100 percent. The main benefits addressed by this research included improvements in operator efficiency through fuel and flight-time savings and additional cargo revenue potential, and improvements in system efficiency through better cruise level assignments (closer to optimal flight level).

[1] The Bureau of Transportation Statistics reported that the average price of airline fuel cost for international service was $0.57 per gallon in 1999, $1.19 per gallon in 2004 and $1.41 per gallon in the first quarter of 2005.

1.1 Organization of this Document

This report is organized as follows:

- Section 1, *Introduction*, summarizes the challenges that inspired this research effort, and its scope.

- Section 2, *Benefits Mechanisms*, describes the current practices in NAT OTS environment, and elaborates the benefit mechanisms enabled by reducing separations between equipped flights.

- Section 3, *Modeling*, describes the models used to analyze benefits from reduced separations, including future demand generator, track selection model, fuel requirements models, and simulation model of airspace track operations.

- Section 4, *Results*, discusses the outcomes with emphasis on fuel and time requirements and savings for the investigated scenarios, and additional cargo revenue potential; it also discusses the improvements in system performance, including the percent of total flight duration that flights spend on their optimal flight levels and percent of desired altitude changes than are granted.

- Section 5, *Conclusions*, summarizes the scope and assumptions used in this research effort, and presents the overall annual benefits as a function of demand and equipage levels, and track configurations.

2 Benefit Mechanisms

The primary benefit mechanism enabled by reduced separation standards, is an increase in airspace capacity for the most favorable routings. Increased airspace capacity effectively allows for improving flight efficiency through allocation of optimal or closer-to-optimal lateral routes, flight levels and speed profiles. The resulting operational benefits are obtained through decreased fuel requirements, shorter flight durations, and additional cargo revenue potential.

In addition to improving flight efficiency, reduced separation standards also enable improvements in system performance. For instance, the resulting increase in airspace capacity facilitates improvement in responsiveness to in-flight requests, accommodation of user-preferred routes, and reduction of flight delays. Consequently, it also provides additional room to assist market growth.

Before addressing the specifics of the benefits mechanisms, it is important to understand the current decision making process and considerations that operators face while planning and executing oceanic operations within the NAT OTS. Also, it is important to point out potential improvements in operations that would enable benefits if the separations are reduced.

2.1 Current Practices in Oceanic Flight Planning

2.1.1 Flight Route and Profile Selection

Through a flight planning process, operators negotiate and select a track for each of the flights that traverse the North Atlantic oceanic airspace via the organized track system. The decision about which one of the daily tracks to select is typically made by analyzing the cost of fuel and time required to complete the trip via each of the tracks. However, this decision is also based on the operators' past experience with traffic patterns on a similar day, and their perception of the likelihood of being granted an efficient altitude on a given track.

While within the track system, each flight is required to follow its assigned track, and to maintain the flight level and Mach number specified by the oceanic air traffic controller. The flight level and Mach number are determined by considering the flight's performance characteristics and current weight, and the proximity and relative speed of the surrounding traffic; an example of track operations is illustrated in Figure 2-1.

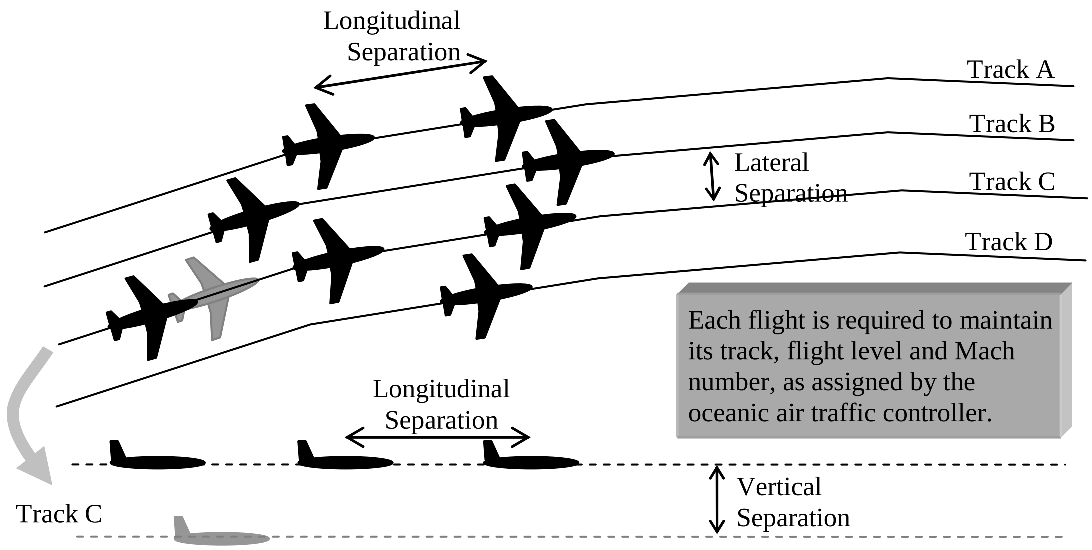

Figure 2-1 Illustration of operations on a track system

All altitude and speed changes must be requested from, and approved by, the oceanic air traffic controller. The feasibility of a requested change is determined by considering longitudinal and vertical separations from the surrounding traffic on the track, and closure rates resulting from different cruise speeds of the successive flights. Under conditions of low traffic density, it is likely that the clearance would be approved; however, as traffic density increases, the separation requirements begin to constrain such changes either due to immediate violations (e.g., an aircraft is within the separation distance at the flight level above) or projected violations (e.g., a faster aircraft is right behind the "empty" spot at the level above); both cases are illustrated in Figure 2-2. In the latter case, a climb could have been accommodated at the expense of speed control on the trailing aircraft.

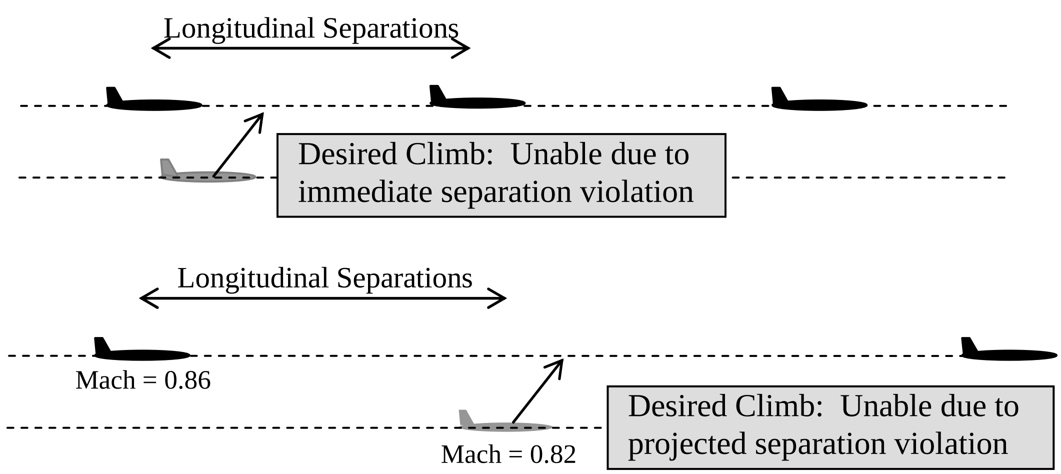

Figure 2-2 Illustration of aircraft unable to climb due to nearby traffic

As the flight progresses, the weight of the aircraft will decrease as fuel is consumed, which leads to an increase in the optimal altitude (under zero winds). Therefore, an efficient flight profile would require a continuous change of altitude (a.k.a., cruise climb) corresponding to the most efficient operations. However, flights are typically limited to fixed flight levels, necessitating a transformation of cruise climbs into a series of step climbs; both are illustrated in Figure 2-3. The exact locations of the steps for any given flight will be dependant on the winds, weight and Mach number.

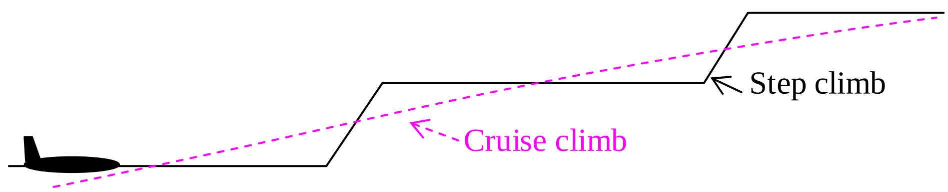

Figure 2-3 Cruise Climb vs. Step Climb

The exact locations of the actual (as opposed to optimal) steps for any given flight will also be dependant on the traffic density. In NAT OTS, depending on the winds on a particular day, certain tracks are typically preferable over others. Certain schedules are also preferred as dictated by the passenger demand; for instance, most of the flights from Europe to various destinations in North America are morning departures. This leads to periods of high density of flights along the most preferred track(s), during which flights are operating near separation limits and the likelihood of receiving an altitude clearance is low. Moreover, flights typically operate with limited voice communications through high-frequency radio, and with limited surveillance using infrequent position reports. As a result of such cumbersome communications, limited traffic awareness and often low likelihood of requests being granted, operators tend to simply maintain their assigned altitudes and speeds, and only infrequently request modifications. In fact, the vast majority of the flights are even planned to operate at a constant altitude throughout the NATOTS: according to the ODAPS ICAO Flight Plan data for October 2, 2004, about 90% of flights file single altitude for the track portion of their flight.

2.1.2 Flight Efficiency Control

Once a track has already been determined, a flight operator can control the efficiency of operations only through a combination of speed and flight level selection. However, flight efficiency does not mean the same to all operators, and even the same operator values various decision variables differently depending on the current status of the flight, such as remaining fuel on board or accumulated flight delay. Some operators tend to put a premium on time, while others consider fuel to be more important. The tradeoff that operators are willing to make between these two is dependent upon the relative cost of fuel and cost of time to that particular operator and that particular flight. A simple measure air-carriers use to determine this relative cost is the cost index (CI), defined as a ratio of time cost ($/hr) to fuel cost ($/lb). Implemented within flight management systems, CI effectively illustrates a trade-off potential between extending trip duration to reduce fuel costs on one hand, and burning extra fuel to maintain flight time on the other. Aircraft model and engine fuel flow characteristics are critical for determining the proper value for CI for a flight. In addition, since CI directly impacts trip duration, the value of time and the value of preserving planned schedules and fleet/crew rotations are also critical for determining its proper value.

Clearly, the exact values of cost indices do not only vary from one operator and flight to another, but also from one situation to another. For example, a zero-value CI will be used by pilots in situations when the remaining fuel is much more significant consideration than delaying an aircraft full of passengers, such as unexpected strong winds on route. But, in situations where fuel costs is less important than other relevant considerations, the value of the chosen CI can be quite high; for instance, maintaining crew or airframe rotation schedules. Unofficial sources[2] report a range of CI values from 80 to 300 for oceanic flights on B747-400; the most frequently reported value was 100, and higher than 250 is used in time critical situations.

Controlling flight efficiency through an application of CI is simplified in an oceanic environment, where these flights are typically flown at a constant Mach number. This leaves the choice of altitude as the single degree of freedom left for managing the efficiency of operations.

Given an operating condition for a flight (e.g., weight, Mach number), fuel consumption can be expressed as a function of altitude. Ground speed is also a function of altitude, and depends on the variation of both temperature and winds at given altitude. These factors produce the following expression for total cost per nautical mile, normalized by the cost of fuel.

$$\frac{\$/nmi}{C_F} = \frac{FF}{V_g} + \frac{C_T}{C_F}\frac{1}{V_g}$$

Where:

C_F = cost of fuel in $/lb

FF = fuel flow in lbs/hr

V_g = Ground speed in nmi/hr

C_T = cost of time in $/hr

By applying CI (note that its unit is 100 lb/hr), the cost of time can be expressed as a function of the cost of fuel:

$$C_T = CI * C_F$$

As a result, the total cost per nautical mile can effectively be expressed as a function of the cost of fuel, CI and V_g:

$$\$/nmi = \frac{C_F}{V_g} * (FF + CI)$$

Ground speed is a function of winds and airspeed (Mach number), and the fuel flow is a function of aircraft weight, speed and altitude. Therefore, the total cost is normalized to incorporate the value of both time and fuel, and is effectively expressed as a function of

[2] Bluecoat Digest Cost Index Survey at http://www.bluecoat.org/

altitude, fuel cost, and weight for a given Mach number and winds. Consequently, as illustrated in the figure below, flight costs can be optimized by selecting the appropriate altitude.

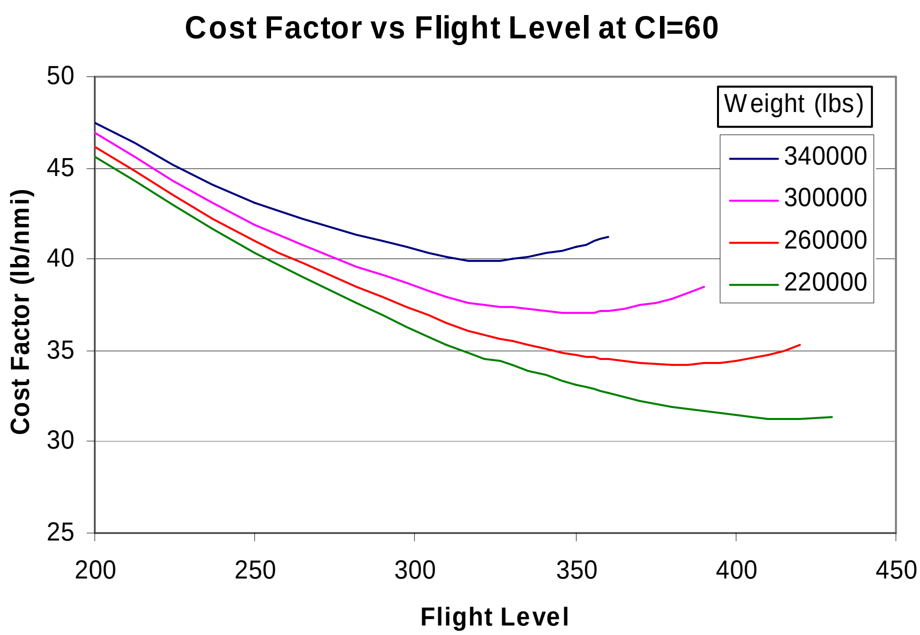

Figure 2-4 Example Total Costs as a Function of Flight Level and Aircraft Weight (M=0.82)

The efficiency of flights using NATOTS is significantly affected by winds. For instance, Figure 2-5 illustrates the wind profile at various latitudes in the middle of the track system on October 2nd, 2004. Clearly, some altitudes are much more preferable than others, facilitating considerate time savings through optimization of altitude selection. Therefore, by using the cost index, an operator can exchange time savings for fuel savings to effectively decrease its total cost. Note that depending on the flight direction, the wind can help save fuel as well by requiring fewer pounds of fuel per nautical mile of ground track; that is why the CI is normalized in ground speed.

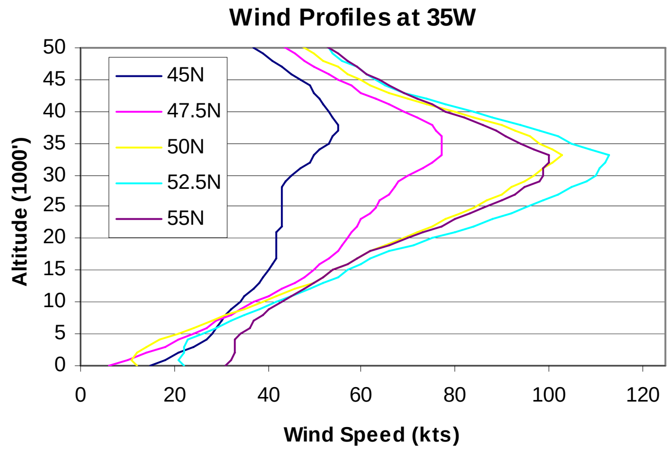

Figure 2-5 Wind Profiles within the NATS OTS

2.1.3 Fuel Requirements

Air carriers are required to follow Federal Aviation Regulations (FAR) part 121 §121.645(b) to determine fuel supplies for an oceanic flight. These regulations specify that:

> (b) For any certificate holder conducting flag or supplemental operations outside the 48 contiguous United States and the District of Columbia, unless authorized by the Administrator in the operations specifications, no person may release for flight or takeoff a turbine-engine powered airplane (other than a turbo-propeller powered airplane) unless, considering wind and other weather conditions expected, it has enough fuel--
>
> (1) To fly to and land at the airport to which it is released;
>
> (2) After that, to fly for a period of 10 percent of the total time required to fly from the airport of departure to, and land at, the airport to which it was released;
>
> (3) After that, to fly to and land at the most distant alternate airport specified in the flight release, if an alternate is required; and
>
> (4) After that, to fly for 30 minutes at holding speed at 1,500 feet above the alternate airport (or the destination airport if no alternate is required) under standard temperature conditions.

In addition, FAR part 121, §121.647 lists the following factors for computing the required amount of fuel:

> (a) Wind and other weather conditions forecast,
>
> (b) Anticipated traffic delays,
>
> (c) One instrument approach and possible missed approach at destination,

(d) Any other conditions that may delay landing of the aircraft.

Note that an operator may be granted a deviation from FAR 121.645(b)(2) for the dispatch or release of turbojet aircraft in extended overwater operations under the provisions of OpSpec B043 or OpSpecB044 (FAA Order 8400.10 Volume 3 Ch.1). Such flights can slightly reduce their fuel supply requirements while maintaining an adequate level of safety. However, these fuel calculations are less conservative and, therefore, are not considered in this research effort.

2.1.4 Cargo Calculations

The amount of cargo that can be carried on a flight is determined as the minimum of the following two values: (1) difference between the maximum take-off weight and the combined weight of the passengers on board, flight fuel requirements and aircraft (operating empty weight); and (2) difference between the maximum landing weight and the combined weight of the passengers on board, reserve fuel requirements and aircraft (operating empty weight). Clearly, ability to reduce fuel requirements enables operators to transport additional cargo and increase the flight revenue potential. This, of course, is true only if the demand for transporting cargo is sufficient. According to the FAA Oceanic Directorate, air carriers have already indicated that they would substitute all weight resulting from fuel savings with additional cargo[3].

The additional cargo potential may be estimated by comparing the initial and landing weights a flight would have with typical fuel consumption (for example, within a baseline system), to the initial and landing weights it would have if reducing its fuel requirements is possible (for example, within a future system with reduced separation standards). With this approach, it is assumed that the carrier would use all the weight that becomes available as a result of fuel savings and replace it with additional cargo.

This methodology is based on the Breguet range estimation[4], which uses the following equation to estimate a range for a flight:

$$R = \frac{V}{C_T} \frac{L}{D} \ln \frac{W_i}{W_i - W_f} \qquad (1)$$

Note that R represents the range, V the ground speed, C_T the coefficient of thrust, L the lift, D the drag, W_i the initial, and W_f the final (landing) aircraft weight.

On the other hand, the range can also be approximated as the overall flight time times the average ground speed, or as:

$$t \approx \frac{R}{V} \qquad (2)$$

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[3] FAA, May 2001, ATOP Acquisition Program Baseline, p. 4-1: “Discussions with airlines indicated that they attempt to use all available weight so that the replacement percentage is actually in the 95 to 99 range (of fuel savings).”

[4] For more detailed explanations, please refer to E. Torenbeek, “Synthesis of Subsonic Airplane Design,” Delft University Press, Boston, 1982, pp. 157. eqn. 5-40

The following substitute can be introduced:

$$k = \frac{D * C_T}{L} \tag{3}$$

By substituting (2) and (3) into (1), we get the following:

$$\frac{W_f - W_i}{W_i} = e^{-kt} \tag{4}$$

By assuming that the value of k is the same for a baseline flight and its corresponding future flight, it is possible to estimate the final weight of each flight if the saved fuel was replaced by the additional cargo. This cargo potential may be estimated by determining k for the flight within a future environment, then substituting its initial weight, Wi(f)', with the initial weight that the flight had within the baseline environment, Wi(b)= Wi(f)", and finally determining the corresponding landing weight, $W_f(f)$". Figure 2-6 illustrates the methodology used.

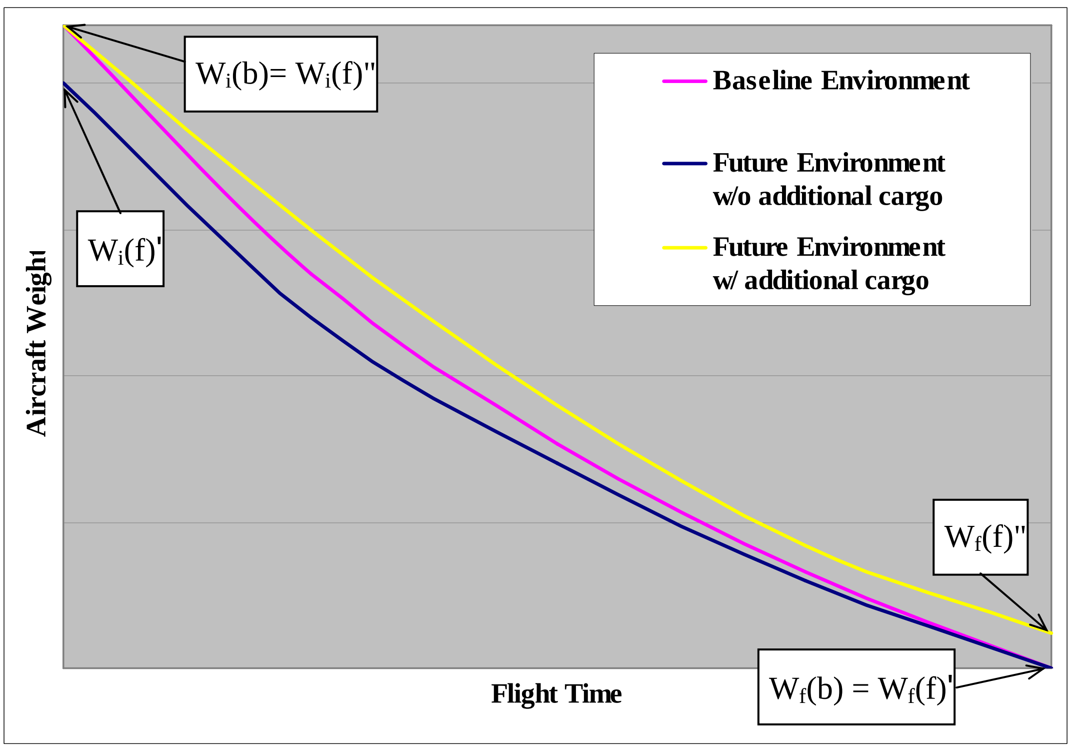


Figure 2-6– Determining Additional Cargo Potential through an Application of the Breguet Range Equation

The first step in estimating the additional cargo potential involves determining the fuel consumption for a flight within the baseline and future environments, assuming the same final (landing) weights ($W_f(b) = W_f(f)'$) and appropriate flight profiles that were available within the corresponding environments. Due to lower separation standards within the future environments, the flight is expected to follow an improved profile that is closer to its optimal (as compared to the profile within the baseline environment). As a result, it is likely to consume less fuel, and, thus, have lower initial (take-off) weight, or $W_i^B > W_i^F$.

The difference between the initial weights assumed for the two cases represents the fuel savings resulting from the improved altitude profile within the future environment.

However, only a portion of that weight can be replaced by cargo; the remaining weight must be reserved for the additional fuel required to complete the same improved profile but with a heavier aircraft at take-off. Therefore, the next step involves estimating the final weight $W_f(f)''$ or weight that the flight would have within the future environment if its take off weight is equivalent to the initial weight within the baseline environment, i.e., $W_i(b) = W_i(f)''$. Since the duration of the flight and the Breguet coefficient for the future environment are already known, the new final weight can be estimated as:

$$W_f(f)'' = (1+e^{-kt}) * W_i(b)$$

Consequently, both amount of fuel saved by flying an improved altitude profile and the additional cargo potential can be easily determined as:

$$\text{Fuel Saved} = W_f(f)'' - Wi(b)$$

$$\text{Additional Cargo Potential} = W_f(f)'' - W_f(f)'$$

2.2 Operational Benefits

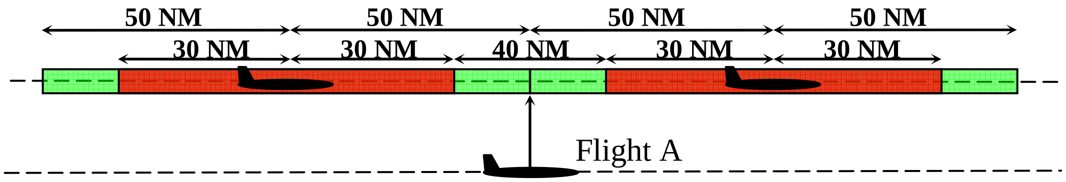
Through an increase in airspace capacity, reduction in separation standards enables increased operator flexibility and more efficient oceanic operations. In particular, flexibility of lateral route selection is increased; this allows aircraft to fly a trajectory that more closely meets operator's objectives. Also, flexibility of altitude and speed selection is improved, which allows aircraft to operate closer to their optimal profiles for longer durations. The resulting operational benefits are obtained through decreased fuel requirements, shorter flight durations and additional cargo revenue potential.

For a given demand level, the increase in airspace capacity also allows operators to adjust schedules and route planning with a goal of reducing the frequency and impact of traffic constraints (interactions with nearby flights).

However, these benefits are limited by the frequency and distribution of equipped flights within the same airspace. In fact, it is crucial not only to have at least two equipped flights but two successive equipped flights for potential benefits to be realized. Therefore, it is important to investigate the sensitivity of benefits to various levels of operators' equipage for a given demand level to be able to understand the true potential of improvements introduced by reduced separations.

2.2.1 Benefits due to Fuel Savings

Reduced separations typically enable more flights to access more efficient flight routes and profiles. Reduced longitudinal separations allow higher density of traffic on the preferred tracks and, thus, enable more efficient routing for more flights than currently possible. In addition, reduced longitudinal separations effectively enlarge the window of opportunity for a flight to climb to a higher flight level and, thus, facilitate achieving more efficient altitude profiles. For instance, in the example illustrated in the figure below, a reduction of separations from 50 NM to 30 NM will effectively open a 40 NM long segment on the higher flight level to which Flight A can climb without causing any separation violations; the same segment would actually be a single point equally spaced from the two flights cruising on the higher flight level in the case of longitudinal separations being 50 NM. However, this mix of higher density and increased opportunity is limited by FL capacity: if flights fill up the capacity of an observed FL, there will be no more opportunity for additional flights to climb to the same FL.



In addition, due to controller/pilot communications being facilitated by datalink, flight crews on an equipped airframe will be more likely to request climbs. Consequently, operators will be able to improve their flight profiles by both *planning* and *accomplishing* altitude and speed profiles that are at, or close to, the corresponding optimal profiles. This benefit is already demonstrated by the higher rate of altitude changes among the datalink equipped flights in ZNY, where operators already plan and request altitude changes on a regular basis. For instance, the FAA Oceanic Performance Dashboard reported 69% for datalink vs. 58% for HF altitude change requests in ZNY[5] from May 2004 through March 2005; in addition, the response times for these clearances (granted clearances only) were 4.2 min vs. 8.9 minutes, respectively.

Lower lateral separations may also enable establishing additional tracks within the same airspace, which would result in further capacity improvements. Furthermore, lower lateral separations allow for establishing more tracks that are closer to the preferred winds and have higher fuel and time efficiencies. However, in a mixed equipage ATOP environment, reducing lateral separations on a fixed track system is restricted by the applicable separations between the non-equipped flights. In other words, to ensure no separation violations at any time, the tracks must be separated at least as much as the highest lateral separations demand. Depending on the overall equipage level, additional efficiencies may be obtained by physically separating the flow of the equipped flights onto separate tracks, a.k.a. segregated tracks. In this case, as illustrated in Figure 2-7, the lateral separations between such segregated tracks (presented in red) are appropriately reduced (Sep A), whereas the lateral separations between the (regular) tracks available to all flights remain restricted by the lateral separation standards between the non-equipped flights (Sep B). Consequently, the segregated tracks can be placed closer to each other and balanced around the most optimal/fuel and time efficient track, thus providing not only more tracks but more tracks with higher fuel and time efficiencies.

[5] Note that these statistics are generated for the non-track MNPS ZNY; due to rare occurrences of NATOTS traversing through ZNY airspace, the corresponding statistics applicable to track system were not available.

Theoretically, the separations between a track available only to the equipped flights[6] and a track available to all flights could also be reduced (Sep C); however, such separations would be hard to implement in practice due to having to combine different type of separations applicable to differently equipped flights (distance-based and time-based longitudinal separations). Therefore, this research effort assumed that only two lateral separations standards would be applied: Sep A and Sep B. In other words, the separations between a segregated and a regular track would be the same as the separations between two regular tracks, or Sep C = Sep B.

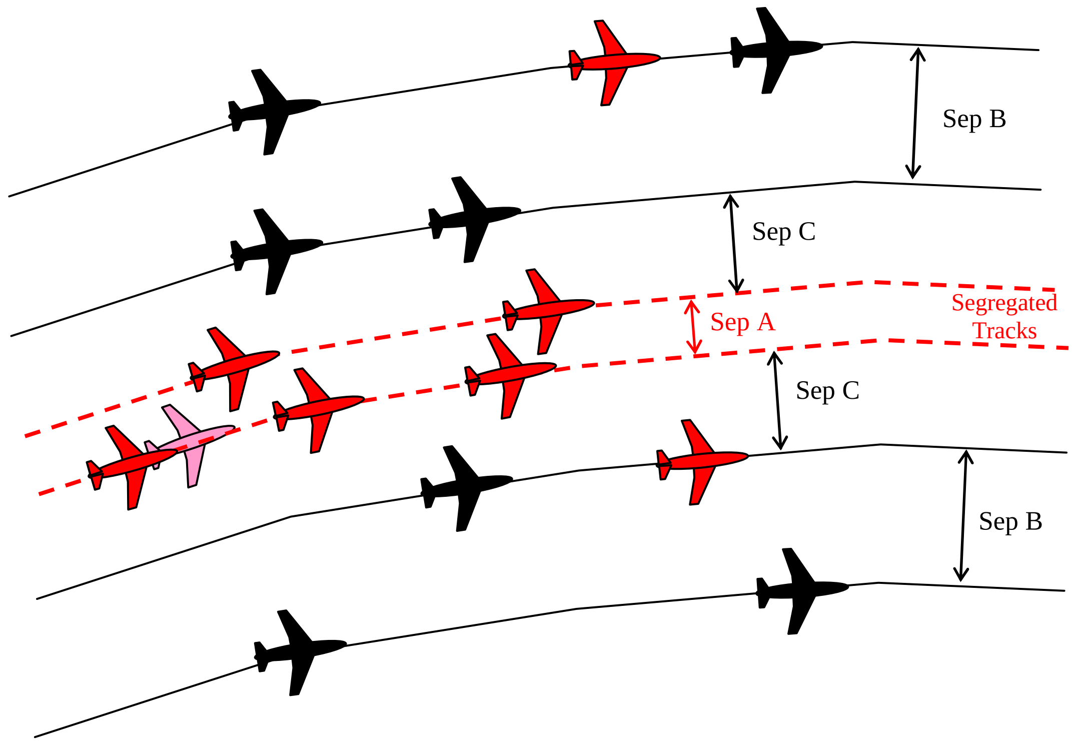


Figure 2-7 Mixed equipage environment (equipped flights presented in red)

Traffic density and flight interactions on a segregated track will increase with increased equipage levels; simultaneously, traffic density and flight interactions on the regular tracks will decrease (Figure 2-8). As a result, at certain levels of equipage, the average benefits to equipped aircraft may start decreasing simultaneously with the average benefits to non-equipped aircraft increasing. At this point, new segregated track(s) would need to be implemented to accommodate the increased levels of equipage without penalties to the equipped operators.

The improvements in fuel efficiency will generally be greater for the equipped flights due to their greater flexibility in choosing routes, and altitude and speed schedules. However, even some of the non-equipped flights will be able to benefit. On the other hand, some flights may experience penalties regardless of their equipage. This is due to a new distribution of flights under the new procedures, as accommodated by the reduced

[6] Such tracks are reserved only for the operations of equipped flights, and will be further referred to as *segregated tracks*

separation standards. All flights will pursue their optimal routes and profiles by using FIFO rule, unless constrained by the nearby traffic. Consequently, the flights with improved routes or profiles will open previously occupied spots for other flights to occupy, regardless of their equipage. As a result of such redistribution of all flights over the track system (i.e., track/altitude combinations), even the non-equipped flights could achieve improved profiles and, thus, fuel saving benefits. Similarly, some flights may not be able to fly the same routes or profiles as before, and, regardless of their equipage, may be constrained to even less efficient routes/profiles.

In addition to being affected by traffic demand, achieved operational improvements are dependant on the frequency and distribution of the equipped flights across the track system. For instance, establishing tracks closer to each other is only possible if they are dedicated for the operations of the equipped flights only; however, even if the separations between the tracks remain the same as today, the equipped flights will still be able to improve their routes and altitude and speed profiles by utilizing higher track capacities.

Finally, it is important to point out that there are two distinct benefits mechanisms due to fuel savings. First, each individual flight can potentially achieve more efficient operation by improving its route, and altitude and speed profiles; consequently, its fuel requirements will be lower. Moreover, each flight will be able to achieve these fuel savings repeatedly, providing for more accurate estimation of fuel requirements on its route and, thus, enabling a decrease in its contingency fuel. Therefore, the predictability of contingency fuel is improved over time, which results in lower average and variance of the fuel carried on each flight flying the observed route, and in reduced direct operating costs.

2.2.2 Benefits due to Time Savings

Small variations in flown route and altitude profile can significantly affect both fuel and time efficiencies of a flight on NAT OTS; this is due to high traffic density and significant effect of the winds. Through reduced separations and, thus, increased capacity of track system, more flights can follow an improved route and altitude and speed profiles, and, therefore, achieve simultaneous savings in both fuel and time. Furthermore, by using CI, an operator can additionally trade between time savings and fuel savings to even more effectively decrease its total cost.

As in the case of benefits due to fuel savings, there are two distinct benefit mechanisms due to time savings. First, each individual flight can potentially achieve more efficient route, and altitude and speed profiles; consequently, its time on route will be shorter and direct operating costs lower. In addition, each flight will be able to achieve these time savings repeatedly, providing for more accurate estimation of time on route. Therefore, the predictability of time on route will be improved, which results in improved on-time performance. It also facilitates air-carriers in adjusting their schedules to maximize both time and fuel savings by strategically positioning their flights to reduce the impact of traffic interactions.

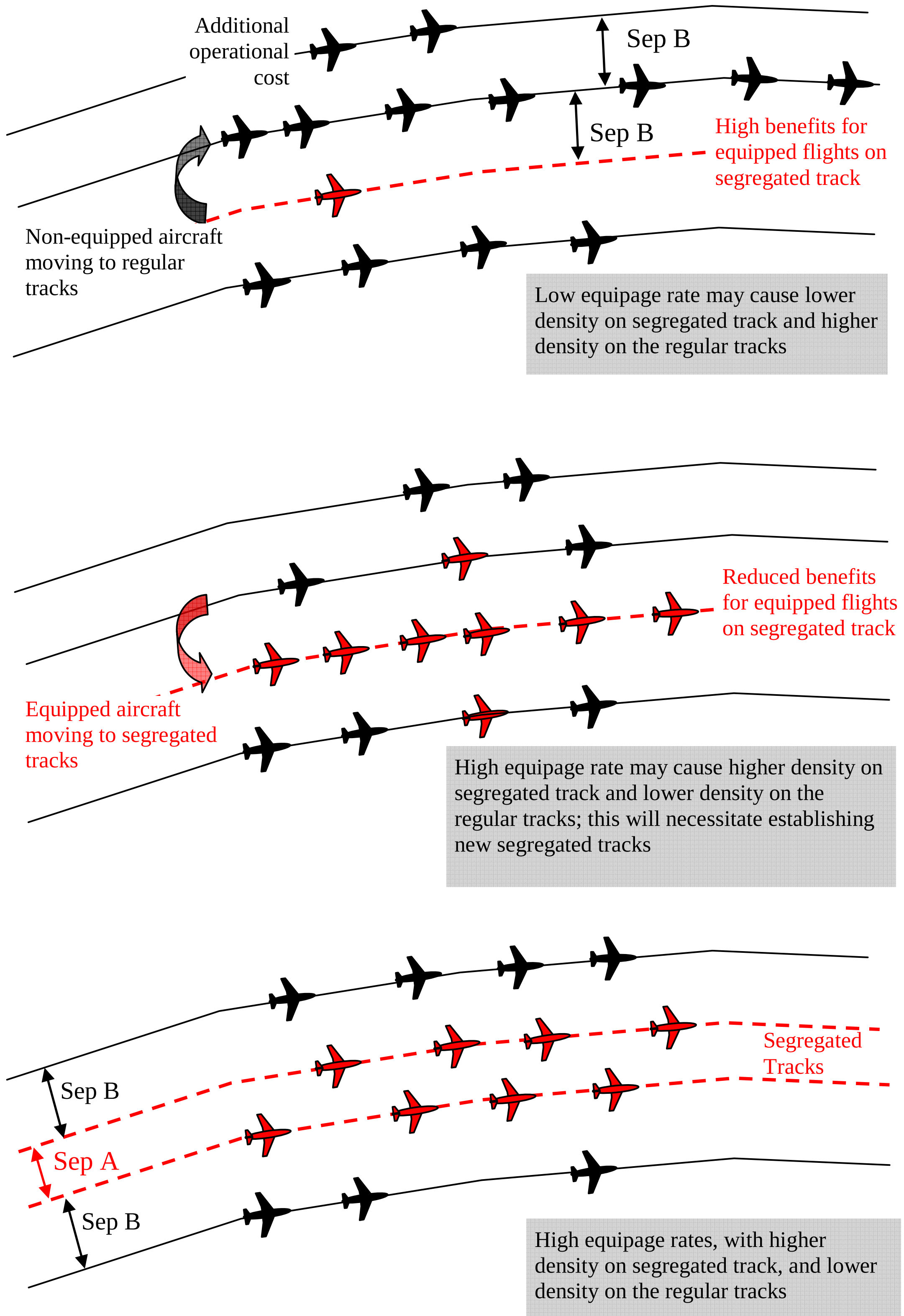


Figure 2-8 Sensitivity of Benefits to Equipage Rate

2.2.3 Additional Cargo Revenue Potential

A reduction in the expected fuel consumption on any given route allows carriers to potentially increase cargo revenue for those flights that were operating at maximum takeoff weight: the operator can substitute a portion of the saved fuel by revenue-generating cargo. The impact of this additional revenue potential is even more significant than the fuel cost savings, due to the unit cargo revenue being a magnitude higher than the unit fuel cost. For instance, the average unit cost of fuel on international flights in 2001 was $0.12/lb[7], as opposed to the average unit revenue of $1.60/lb of additional cargo[8]. Note that the BTS reported the average unit fuel cost of $0.18/lb on international flights in 2004.

2.2.4 Other Considerations

It is important to point out that decision making based on the overall benefits of reducing the separations in an oceanic environment with mixed flight equipage must be based on the combined impact on non-equipped and equipped aircraft. For instance, a decision about establishing a segregated track or introducing new segregated tracks would require consideration of the global impact upon the system. Such decisions must also involve consideration of the airframe-specific benefits, as these will likely lead to different decision points.

For instance, in the case of small equipage rates, equipped flights could achieve significant benefits if flying along segregated tracks and essentially no benefits if segregated tracks are not available. This indicates a motivation potential for operators to equip. However, establishing a segregated track in a low equipage environment would produce significant penalties to the unequipped aircraft as a result of the increased density caused by the segregation of equipped and non-equipped flights. The net benefit in this case may even be negative. On the other hand, with increased equipage rates, the benefits of flying along a segregated track are likely to decrease; however, the offloading of equipped flights from other tracks to the segregated track is likely to cause increased benefits to the remaining (mostly non-equipped) flights flying along these regular tracks. At some point, the equipped aircraft must determine whether to operate on a segregated track at all, and possibility of introducing new segregated tracks must be considered. The number of the segregated tracks is, thus, a strong function of the equipage rate as there must be a match between the demand for, and supply of, such track(s). Figure 2-8 illustrates these considerations.

In addition, optimal tracks are not the same for all flights, and are based on the geographical locations of the airports of origin and destination, as well as on the airframe model. For instance, trans-Atlantic flights from San Francisco to London are not likely to desire the same tracks as flights from Miami to Madrid (unless the winds are highly concentrated and very strong). The criteria for selection of segregated track(s) will affect the achieved benefits on each individual flight. For example, if segregated tracks are

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[7] Source: Bureau of Transportation Statistics (BTS)

[8] Source: Aviation & Airspace Almanac, 2001, and ATOP Acquisition Program Baseline, 2001

selected upon the overall track-traffic demand, the benefits will be higher for the equipped flights on the popular routes. On the other hand, if the major criterion for segregated track selection is to motivate the operators to equip, segregated tracks might be selected by considering only the routes of the equipped flights.

3 Modeling

3.1 Data Sources and Issues

The NATOTS spans across multiple controlling states; these typically include United Kingdom (Shanwick OAC) and Canada (Gander OAC), and, depending on weather on a particular day, may also include United States of America (New York Oceanic FIR). Each of the three controlling states has a unique and independent flight data processing system or even multiple systems that collect air traffic related data. Although bordering controlling states communicate with one another, it is rare that states share data due to the sensitivity of the information. As a result, flight data collection and analysis is a rather challenging task, for it requires not only merging different formats for numerous types of messages used to store data, but also removing duplicate, incomplete and sometimes even contradictory information about the same flight.

Flight data used in this research effort were collected by the following two systems: (1) the Enhanced Traffic Management System (ETMS), and (2) the Oceanic Data Analysis and Planning System (ODAPS). For each of these systems, a program was developed to parse the system's distinct formats for several message types and to extract the essential information about each of the flights, including aircraft id, origin and destination airports, aircraft model and equipment. Also, the position reports were collected by recording time, altitude, speed, and position in waypoint or degrees. Finally, the information relevant to the track traffic was extracted and merged into a single database.

Position reports typically contain three aircraft positions: (1) the current aircraft position known as the reported 'over' (OV), (2) the next position known as the 'expected over' (EO), and (3) the following next position (NP). In addition to the time of flying over a waypoint, each position report must contain current location and altitude. The location is expressed as latitude/longitude combination, or as the published waypoint name. However, formats used to report latitude and longitude can be different for different airspace regions and are also dependant on the predominant flight direction. For instance, in the NAT oceanic airspace, latitude is expressed in degrees only for the traffic traveling predominantly north or south, and in both degrees and minutes for the traffic traveling east or west. The opposite is true for reporting longitude: east or west traffic uses only degrees, and north or south traffic both degrees and minutes. Also, the position time is expressed using UTC as reference and four digits: two digits are used for hour (00-23) and two for minutes (00-59). Finally, the altitude is expressed as a flight level using a three digit format. It is important to point out that even though operators should follow the described formats for location, time and altitude reporting, it is common to see modified formats as well.

Enhanced Traffic Management System (ETMS)

The Enhanced Traffic Management System (ETMS) is an operational system developed to assist FAA in air traffic flow management and strategic control of traffic flow. The ETMS collects numerous types of messages exchanged between cockpit and air traffic control, including flight plans, flight plan amendments, airport departure and arrival messages, radar positions, oceanic reporting positions, etc. Figure 3-1illustrates the coverage of oceanic position reports found in the ETMS dataset, where each red dot indicates an oceanic position report[9].

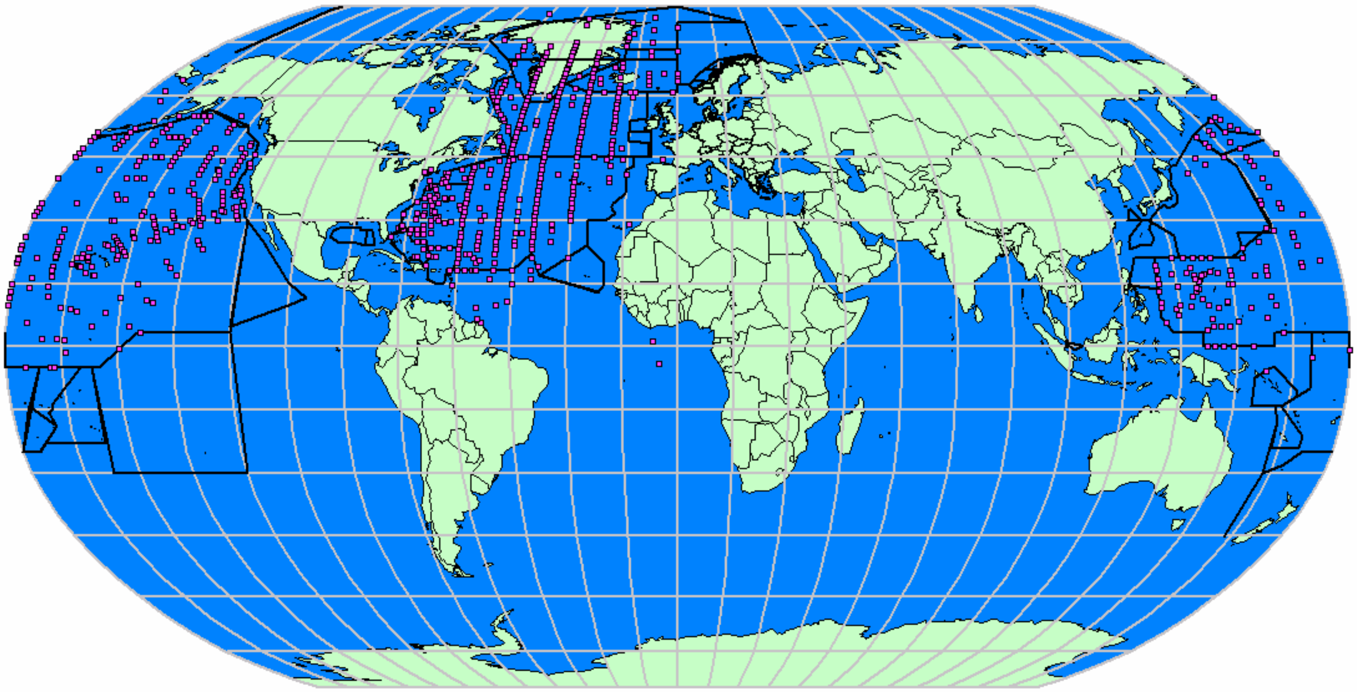

Figure 3-1 ETMS Oceanic Position Reports

Even though the ETMS contains flight data for the flights throughout the NAT oceanic region, ETMS proved not to be sufficient to provide the necessary flight information for this research effort. Closer examination of ETMS data reveled incomplete air traffic information. In particular, many flights were missing their flight plans, or had only a few points reported. In addition, datalink equipped flights were completely missing, and number of HF position reports were questionable. Figure 3-4 provides few examples[10] of problems with information stored in position reports; note that each row represents an individual ETMS position report, and problem field are highlighted in blue text.

The first three messages are simply missing the information in highlighted fields, whereas the third message reports unrealistic speeds. The message #6 is effectively a forecast of a position report, because the time it was communicated to the ATC is earlier than the reported time at position: 17:00 vs. 17:44 UTC, respectively. Finally, in addition to impossible speed, message #7 also has a suspicious lat/long coordinates, because the next expected position is 5031N/17557E or 4200 nm away (implying that the aircraft flew at a speed of 4240 kts).

Table 3-1 Examples of ETMS Position Report Message with Incorrect Data

[9] In ETMS data the oceanic position reports are indicated by message type "TO".

[10] Due to the sensitivity of operational data, all information that can identify the air carrier or the controlling agency has been removed.

ID	Message Time (MMDDhhmmss)	Speed (kts)	Position Time (DD/hhmm)	Altitude (FL)	Position (lat/long)
1	0110024117	000	**00/0000**	390	4500N/00215W
2	1002134814	426	02/1347	**000**	5800N/05000W
3	1001230027	**000**	01/2308	370	3555N/07044W
4	0105202950	**-27688**	05/2023	330	6400N/06000W
5	1001230918	**9001**	01/2308	320	1653N/14155E
6	**1003170033**	000	**03/1744***	000	2842N / 13926W
7	1001060907	**4240**	01/0604	350	**4158N/07231W****

Oceanic Display and Analysis Planning System (ODAPS)

The Oceanic and Display and Analysis Planning System (ODAPS) records oceanic aircraft positions reported within the New York Oceanic FIR (ZNY) or Oakland Oceanic FIR (ZOA). In addition to reports within the FIR, neighboring FIRs typically forward "courtesy" position reports for flights expected to enter the New York Oceanic or Oakland Oceanic FIR. Figure 3-2 illustrates the coverage of oceanic position reports found in the ODAPS dataset, where each yellow dot indicates an oceanic position report[11] in the New York dataset and the red dots for the Oakland dataset.

The ODAPS database typically does not contain the position reports for the NAT OTS flights because tracks rarely pass through ZNY FIR. However, on days when the track system is established further south than usual, and therefore traverses the ZNY FIR, the corresponding ODAPS dataset will contain the relevant flight plan and position information.

[11] In ODAPS the oceanic position reports are documented in three message types, the reported flight position report 'POS', the reported flight position report with weather information 'AEP, and the air-ground report 'AGM'.

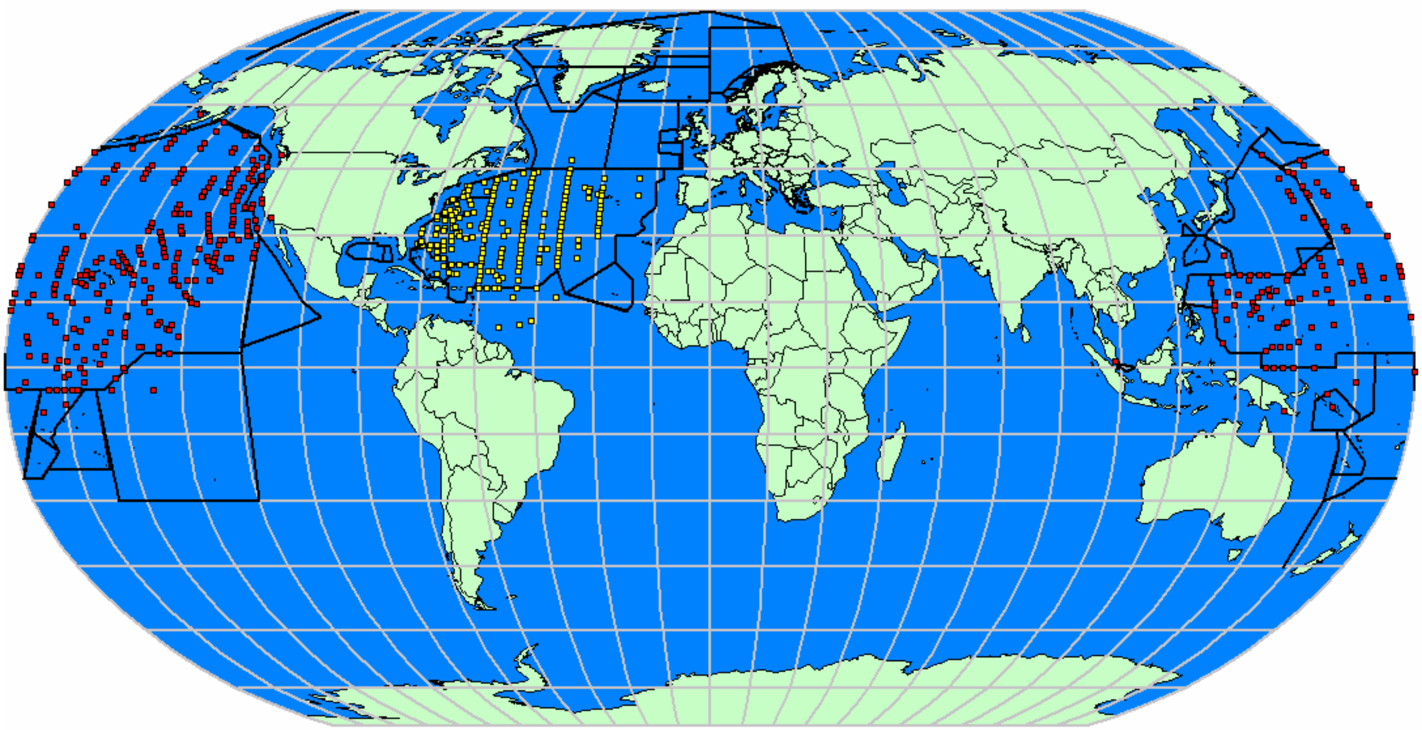

Figure 3-2 ODAPS Oceanic Position Reports

As with the ETMS data, ODAPS data are often incomplete, missing, or inaccurate. In addition to the few examples of inaccuracies in ODAPS data listed in the two tables below, it is important to point out that ODAPS for ZNY also limits the length of messages being stored, which sometimes results in obtaining only partial flight plan information; in most such cases the destination airport code is missing.

Missing the reported over altitude

Message: 021840 POS FI XXX999/OV LETON 1838/EO BROCK 1848/NP TOCCO DT NYC XO A

Message Time: DDhhmm	Position	Position Time	Altitude	Speed
021840	LETON	1838	**Missing**	**Missing**

Missing the reported speed

Message: 010414 POS FI XXX999/OV 30N040W 0413 F360 EO 39N030W 0547/NP 44N020W DT NYC

Message Time: DDhhmm	Position	Position Time	Altitude	Speed
010414	30N040W	0413	360	**Missing**

Oceanic Position Report Processing

Figure 3-3 outlines the process used to prepare the traffic sample database used for the benefits analysis. Note that due to inconsistencies in formats used to store traffic data collected by different systems, data pre-processing is required in addition to data cleaning. This is important because each new source added to this flow-chart requires often significant time to resolve data parsing and merging problems.

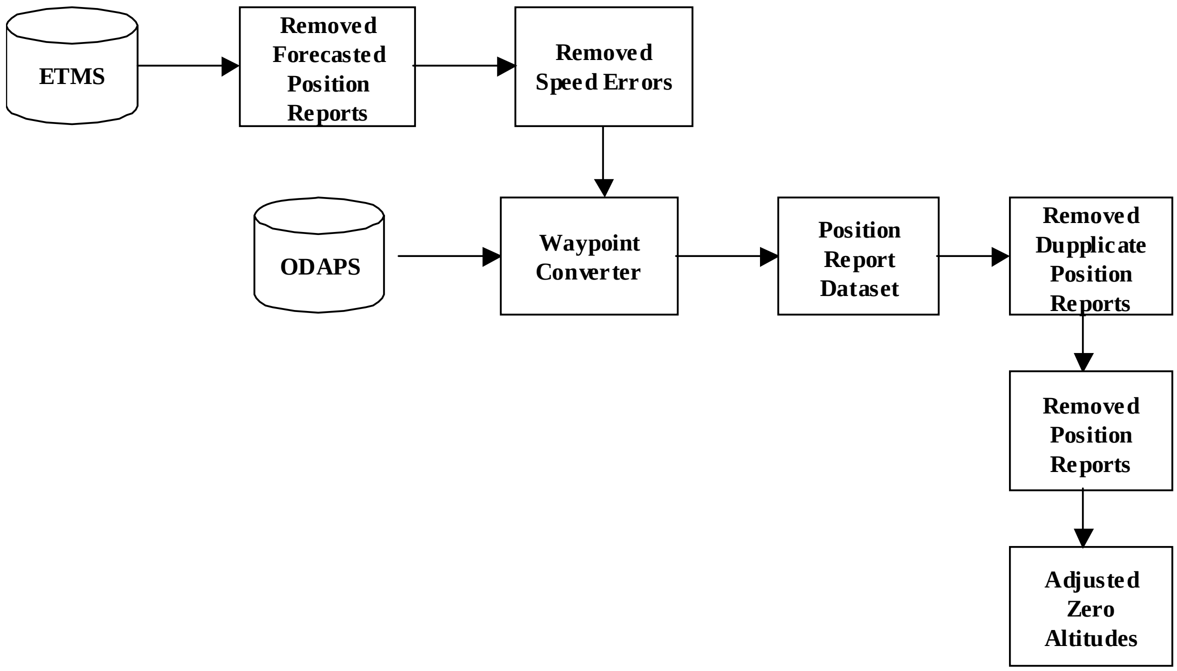

Figure 3-3 Oceanic Position Report Processing

3.1.1 Baseline Traffic Data

Flight plans for the baseline traffic schedule used in this research effort were collected by the ETMS and ODAPS systems for the actual flights performed on October 2, 2004. A total of 564 flights used the track system on that day, distributed as follows:

- 325 early morning eastbound flights, flying along the tracks V through Z (active from 1:00 to 8:00 GMT), and
- 239 afternoon westbound flights, flying along the tracks A through F (active from 11:30 to 19:00 GMT).

According to the filed ICAO flight plans, about 88% of these flights were scheduled, 6% non-scheduled, 2% military, 2% GA, and 1% cargo flights.

As presented in Figure 3-4, the track system on the observed day was mostly contained within the Gander Oceanic FIR and Shanwick OCA; only the tracks A and B also passed through the Reykjavik and Sondrestrom FIRs.

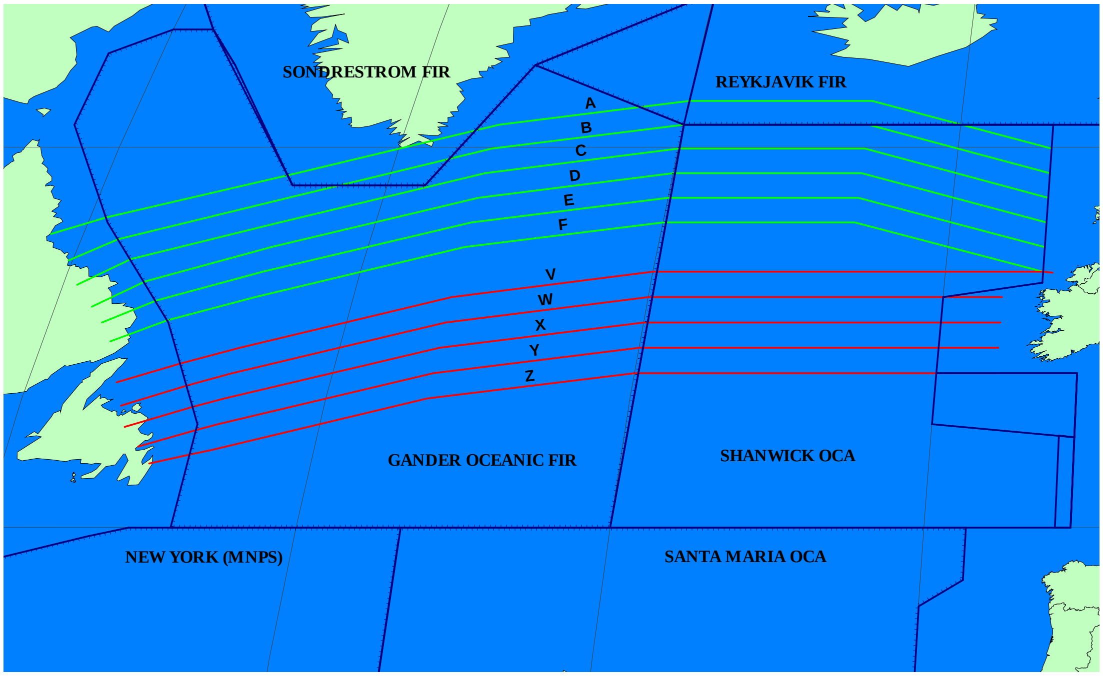

Figure 3-4 North Atlantic Organized Track System October 2, 2004

Due to more favorable winds, the early morning tracks served more flights and had denser traffic. Figure 3-5 illustrates the distribution of flights across the available tracks:

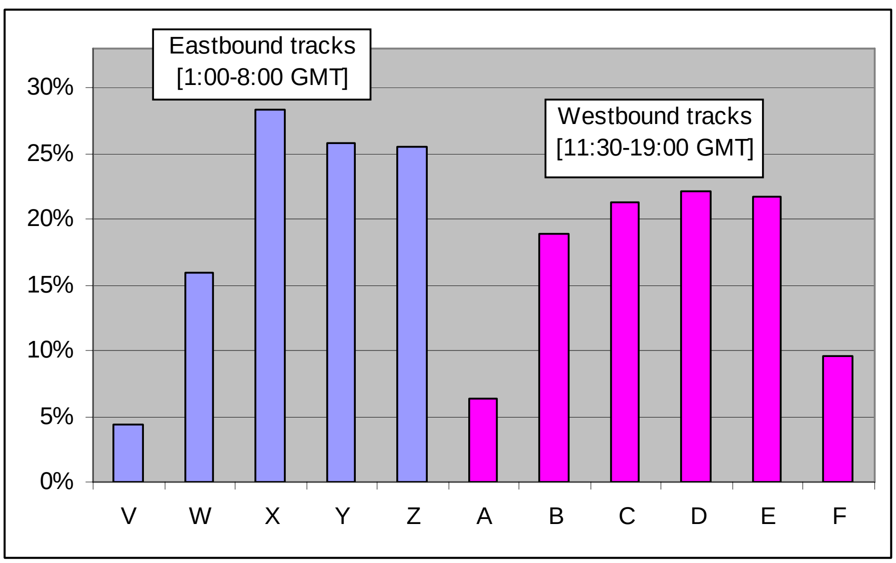

Figure 3-5 Distribution of Flights within NAT OTS on October 2, 2004

The ICAO flight plans filed by the operators indicate that about 25% of all flights were performed on B767-300, 19% on B777-200, 11% on B747-400, 8% on A330-300, 7% on A330-200, 6% on A340-300, 5% on B767-200, and 3% on B757-200. The remaining 17% of flights are distributed across 20 other aircraft models, each with a presence of 2% or less.

Finally, through their ICAO flight plans, the operators reported that about 27% of all flights were ADS equipped, 34% datalink equipped, and 99% capable of operating in RNP designated airspace and routes (the only current requirement in NAT OTS is MNPS capability, which is equivalent to RNP 12.6).

3.2 Assumptions Summary

The following list summarizes the major assumptions used in this research study:

- Flights cannot switch tracks once they have entered the track system; the track that was assigned by the controller at the entry point must be maintained regardless of equipage. Flights can join the track system late, or exit it early, but only if using the outside tracks.
- Track traffic is conducted independent of the traffic on the adjacent tracks. In other words, tracks are always sufficiently spaced, even at turns/heading changes, and flights are capable of maintaining their trajectories with sufficient accuracy to ensure that there are no lateral separation violations.
- Equipped flights will pursue their optimal step-climb altitude and speed profiles, even within the track system, and maintain a distance of at least 30 NM from other equipped and 10 minute Mach technique separations from the non-equipped flights on the same track.
- Non-equipped flights will pursue their optimal altitude and speed profiles as well, but these will be limited to a single flight level while on NATOTS. The required longitudinal separations imposed on non-equipped flights will be the 10 minute Mach technique (approximately 80 NM).
- The 2004 average unit fuel cost[12] published for international flights was used for all flights: average for 2004 was $1.25/gallon ($0.19/lb) [in October 2004, the average monthly unit fuel cost for international flights was $1.39/gallon or $0.21/lb]
- Different CI values are used for different aircraft models, but uniform CI for all operators on a given aircraft model.

3.3 Future Traffic Demand Modeling

Demand levels for future years of interest were determined through an application of the Future Demand Generator (FDG). This model uses the Fratar algorithm to generate a future traffic schedule based on a baseline schedule and growth rates of airport operations, and adjusts the future schedule so that the number of forecasted operations at any of the airports does not exceed its forecasted capacity. The Fratar algorithm is an iterative trip distribution technique used to scale a baseline traffic schedule according to the projected traffic growth at each individual airport; the number of performed iterations is specified by the user.

[12] Source: BTS, http://www.bts.gov/xml/fuel/report/src/tableversion.xml

There are two types of growth parameters that may be used by FDG:

1. An individual growth parameter specified for each of the baseline airports, or
2. A global growth parameter specified for the entire set of the baseline airports.

If traffic forecasts indicate different growth parameters for different airports, FDG uses the FAA Terminal Area Forecast (TAF) file to determine the projected number of operations at major US airports for a future year of interest. A growth factor for each airport is then calculated by considering a baseline schedule and the future traffic levels reported in the TAF. The Fratar algorithm is then used to determine the number of flights for each of the origin-destination pairs in the future schedule. Finally, the schedule is adjusted by determining proper departure times to assure no airport capacity violations.

Since foreign airport growth information is not contained in the TAF, FDG will calculate the average growth factor of large domestic airports (those whose capacities are known) and assign this growth factor to the foreign airports. Alternatively, the TAF file can be augmented with the growth information at foreign airports, if such information is available.

On the other hand, if a global traffic growth parameter is specified, FDG will apply it directly to each origin-destination pair to determine the corresponding number of flights in the future schedule. In other words, since the traffic growth rates are identical for all airports, FDG does not need to calculate the individual airport traffic growth rates; therefore, a TAF file is not needed and the Fratar algorithm is not used. FDG will, however, assure that the future airport capacities are not exceeded while determining the future schedule.

Based on user input, FDG places the flights from the baseline schedule into departure and arrival bin (15 or 60 minutes in duration). Once the future number of flights between each origin-destination pair is determined, the baseline flights are replicated according to the required number of future flights, thus maintaining the preferred time-of-day schedules between city pairs within the time bins.

The user can optionally specify an input file containing the departure and arrival capacity of certain airports in terms of the maximum number of operations per hour for the future year of interest. The future schedule is then constrained to the projected airport capacities by moving flights to adjacent time bins as necessary so that the hourly numbers of departure and arrival operations are not exceeded at the specified airports.

Once the future flights are determined for each time bin, their departure and arrival times need to be adjusted to assure no violations of the airport capacities. First, FDG assigns a takeoff time to each replicated flight by using a uniform distribution within the flight’s departure bin at the airport of origin (15 or 60 minutes long). Then, it calculates the flight’s arrival time by using the duration of the corresponding baseline flight, and determines flight’s arrival bin at the destination airport. These take-off and arrival times are then adjusted if necessary by moving the flight to adjacent time bins at the corresponding airports, so that their capacities are not exceeded.

The FDG generated schedule is identical in format to the baseline schedule; it includes the flight ID, origin, destination, departure time, arrival time, aircraft type, and any other property of the flight[13]. In addition, since the baseline flights are essentially replicated, all information associated with each flight is carried forward to the future schedule; this allows maintaining various flight properties, such as airframe model, flight type, etc.

Since each flight in the future schedule can be traced back to one of the baseline flights, additional information can also be retrieved; for instance, optimal altitude and speed profiles (generated by fuel consumption optimization model, described in Section 3.5, Fuel Consumption Models). It is important to point out that not all of the original flight properties should be used; in fact, future traffic levels and schedules will produce new traffic interactions and new preferred profiles. Therefore, only the *optimal* routes and profiles should be used as unchanged.

In addition, some of the retrieved flight properties should also be adjusted to reflect other expected differences between the baseline and future environments. For instance, FDG cannot create future flights on a market unless the baseline schedule contains at least one flight between the corresponding origin and destination airports. Similarly, FDG cannot generate flights on new aircraft models, and it does not consider projected changes in operators' fleet. Also, FDG does not consider NATOTS capacity limitations while determining the proper departure times for future flights. All such adjustments must be performed through post-processing of FDG generated schedules.

Unfortunately, data regarding international capacity limitations for the future years of interest were not accessible. In addition, traffic growth data was only available on a global level, in terms of overall North Atlantic air traffic growth as opposed to the growth on individual markets or airport combinations. Therefore, for the purpose of this research effort, future schedules were created based only on the NATOTS flights as opposed to overall traffic schedules that include all flights to and from the observed airports.

It is important to point out, however, that international flights typically have priority over domestic flights in terms of flight scheduling due to their higher revenue yield. In addition, they typically have a preferential treatment in terminal areas because these flights burn more fuel and have longer durations (especially oceanic flights). Therefore, growing only the NATOTS traffic was not expected to produce significant differences as compared to the flight counts and schedules that would be produced by a system-wide traffic growth simulation. This approach also facilitates implementation of different demand growth parameters for different groups of operators, such as scheduled, general aviation, military, and cargo flights.

3.3.1 Validation of the Future Traffic Demand Model

3.4 Track Selection Model

Operators typically consider the fuel and time costs of completing the trip via each of the available tracks when choosing a track to file (request from ATC) for a specific flight. In

[13] For instance, flight type designator, such as scheduled, non-scheduled, cargo, GA, or military flight.

addition, this decision is also based on the operators' past experience and the perception of the likelihood of being granted an efficient altitude as well. Track selection often involves negotiation between the operator and air traffic control service provider, and the initially assigned track can be also changed by the oceanic controller shortly before the flight enters the track system. However, such flight plan adjustments are rare and used only to alleviate temporary congestions caused by the stochasticity of track entry times.

Track selection is modeled as a multiple step process based on an exhaustive search algorithm used to determine *the best track that is likely to be available* for each of the flights. It effectively balances track preferences with the traffic interactions under the applicable separation standards.

This approach utilizes the decision tree illustrated in Figure 3-6. This generic track selection tree has a total of T available tracks (with an index t = 1, 2 … T-1, T), and up to N available flight levels on each of these tracks (index i = 1, 2 … N-1, N). $P_{i\,/\,t}$ represents the probabilities of flight level i being favorable and available if the track t was selected (i.e., given the track t), and $Cost_{i\,/\,t}$ represents the aggregated cost of fuel and time of traversing the track system via the track t on the altitude i.

The method used to generate the conditional probabilities is described below.

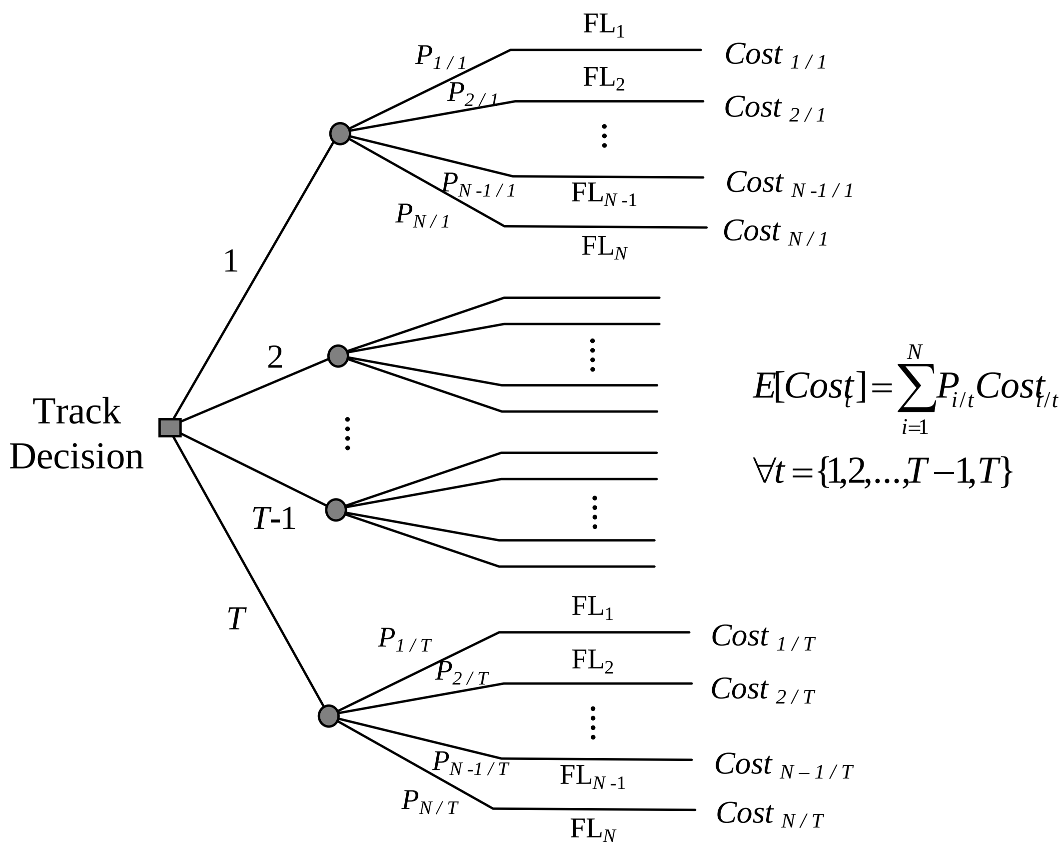

Figure 3-6 Track Selection Decision Tree

The first step involves generating wind-optimized altitude and speed profiles for each of the flights using each of the available track, flight level and speed combinations, and calculating the corresponding total costs. Wind forecasts were used to mimic the information available during the flight planning process. Wind forecasts, exact track locations and actual traffic demand were extracted and processed separately for the early-morning and early-afternoon tracks. For each of the flights, the optimal profile was determined as the one requiring minimum amount of fuel assuming that the flight would maintain the same flight level throughout the track system regardless of its equipage. It would have been more accurate to assume step climb profiles for the equipped flights within the track system; however, the number of different step-climb profiles possible for each of the equipped flights is simply too large to comprehend. This is because of numerous possible locations of start-of-climb-points and magnitudes of flight level changes. Even if only a selected set of different climb profiles is considered, it would still be too computationally intensive and time consuming to select an optimal profile that is also conflict-free throughout the track system. By choosing to work with optimal profiles based on maintaining the same flight level within the track system, the size of the problem is significantly reduced, as is its complexity: safe separations will be assured if there is sufficient spacing at the entry point to the track. Note that these separations also include consideration of speed differential between successive flights, as specified in Chapter 8 of the Order 7110.65P, *Offshore/Oceanic Procedures*.

The results were organized in a multidimensional matrix, and the preferred combinations were ordered by selecting the cruise Mach on each of the track/flight level combinations that resulted in the lowest costs.

In the second step, the preferred track is determined separately for each of the flights using the following process. First, a Monte Carlo simulation is used to randomly perturb departure times for each of the flights using Normal distribution (with a mean of 0s and a standard deviation of 900s), and the resulting flight schedule is processed in chronological order by enforcing the applicable separation standards at track entry. Then, the model assumes that each of the other flights will fly the best available track/flight level and checks if the observed flight *can obtain* each of the flight levels within each of the tracks. This process is repeated 500 times, and a simple count of instances when each of the flight levels (i) on each of the tracks (t) was available to the observed flight is recorded; that number divided by 500 represents the corresponding probability of the flight being able to obtain the flight level i on the track t ($p_{i,t}$).

In general, a zero probability indicates that the corresponding track/flight level combination for a given flight was simply never preferred under the given traffic density and separation standards. Conversely, a probability of one indicates that the corresponding flight track/ flight level combination was the best available option in each of the 500 iterations. Note that this is not necessarily the same as being preferred, for the preferred combination may always be unavailable due to the nearby traffic in each of the iterations.

In the third step, the conditional probabilities of actually obtaining each of the flight levels i on a given track t, $p_{i/t}$, is calculated by assuming that the flight will always choose the most efficient flight level that is available. Therefore, the probability of choosing the most efficient flight level on a given track is equal to the probability of the corresponding track/flight level combination being available to the observed flight, i.e. $p_{i/t} = p_{i,t}$. For instance, if flying along FL350 was the lowest cost option on the track C, then the corresponding probability of actually obtaining FL350 on the track C, $p_{350/C}$, will be equal to the percent of occurrences of FL35 being available in 500 iterations of the Monte Carlo simulations; this is because a flight will always choose the best option if it is available.

The probability of choosing the second most efficient option is then calculated as the product of the probability of the most efficient t option not being available and the probability of the second lowest cost option being available. For instance, if in the previous example the second best option on track C was to fly along FL360, then the conditional probability of choosing FL360 on the track C would be calculated as:

$p_{360/C} = (1- p_{350/C})* p_{360,C}$.

Similarly, the conditional probability of choosing the third best option, for instance FL340 on track C, will be calculated as:

$p_{340/C} = (1- p_{350/C}- p_{360/C})* p_{340,C.}$

Using the proposed method, the conditional probabilities of choosing each of the flight levels on a given track were calculated and stored. Note that it is also possible for a flight to have insufficient spacing from other flights on each of the flight levels on the observed track. The model captures this fact by introducing a fictitious flight level that “accepts” all flights that didn’t have access to any of the flight levels on the observed track. The model counts these instances and calculates a probability of the flight not being able to enter the track in the 500 iterations. Then, it calculates the probability that the flight will actually be required to choose another track ($P_{\bar{t}}$) as follows:

$$P_{\bar{t}} = 1 - \sum_{i=1}^{N} P_{i/t}$$
$$\forall t = \{1,2,...,T-1,T\}$$

The second and the third steps are repeated for each of the flights, and the corresponding conditional probabilities of the track/flight level combinations being both available and favored are stored.

In the fourth step, the expected cost of flying along each of the available tracks is determined as the sum of total costs of entering the track at each of the available flight levels weighted by the corresponding probabilities. The cost of not flying a track given that the track was selected is calculated as 10% higher than the cost of flying the least efficient flight level on that track. As a result, the penalty of having to switch to another track, and experience additional cost in fuel and time, is effectively taken into consideration whenever such an event is likely to happen. If the probability of its realization is small, the corresponding contribution to the excepted cost is minimal (or none, if there is sufficient capacity to accommodate the observed flight on the given track).

Finally, the track with the lowest expected cost is selected as the preferred track for each of the flights under the given traffic demand levels and separation standards.

3.4.1 Validation of the Track Selection Model

There are two main criteria used to validate the Track Selection Model: (1) accuracy of track utilization, and (2) accuracy of selecting a track for a flight. The model was validated using the 2004 flight plan data.

Ability to accurately mimic individual track utilization was investigated by comparing the distribution of flights across the track system based on their flight plans to the corresponding distribution of flights produced by the Track Selection Model. As is illustrated on the example of eastbound tracks in Figure 3-7, modeled track utilization was within 7% of the actual utilization for the same track (track Y).

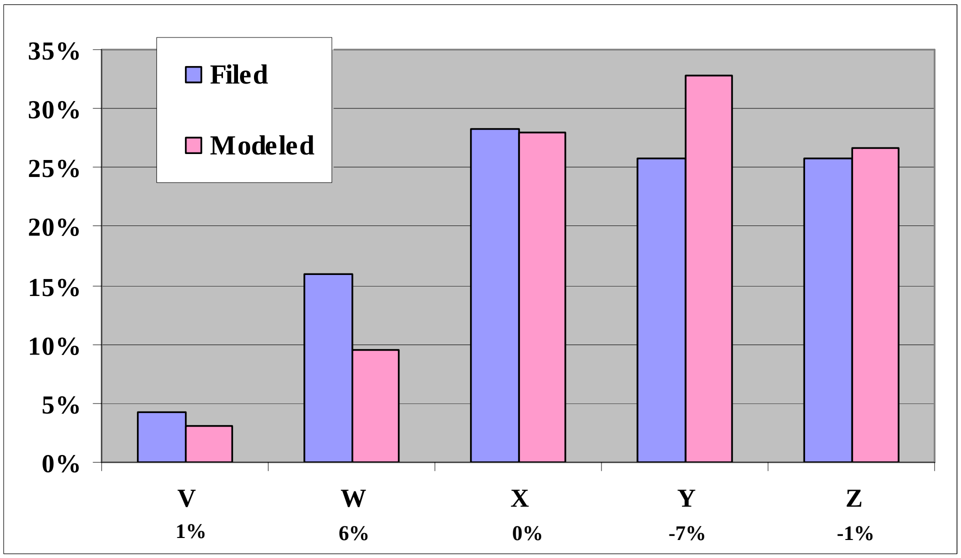

Figure 3-7 Actual vs. Modeled Track Utilization: Eastbound Tracks

The accuracy in selecting a track for a flight was investigated by comparing the actual and modeled tracks that were selected by each of the flights. The focus of this analysis was the accuracy of selecting tracks for individual flights, as opposed to the accuracy of aggregate demand for a track. In about 47% of cases, the model accurately replicates actual track selection, and in about 42% of cases, the model chooses adjacent track. In all other cases, the track selected by the model was the second track away from the flown track.

Note that the smaller the difference in cost between different alternatives, the less accurate a decision tree becomes. In fact, the difference in expected cost of flying the actual and modeled track was only 0.2% on average (with a standard deviation of 0.4%, and median of 0.03%). Also, 95% of all flights had less than 1% difference between the expected cost of flying the actual and the modeled track, and 99% of all flights less than 1.6%.

One of the reasons the expected costs of flying different tracks are not significantly different is granularity of wind data: wind forecast covers the world in a 2.5 degree grid, while the tracks are 1 degree apart. The fuel consumption model uses linear extrapolation to estimate the strength and direction of wind in the missing points. However, the extrapolation cannot capture the sudden changes in wind velocity and direction that are typical for jet streams across the NATOTS. Using the same Track Selection Model with more accurate wind data would likely increase the differences in expected cost of flying adjacent tracks, and therefore improve the accuracy of the outcome.

Also, the fuel requirements model indicates that it is more critical to be able to obtain optimal (or closer to the optimal) flight level than an optimal (or closer to the optimal) track. Therefore, the differences in expected cost of flying adjacent track are additionally reduced by the fact that the current system still has high likelihood of obtaining a sufficiently preferable flight level within each of the tracks.

3.5 Fuel Consumption Models

The two fuel consumption models developed for this research effort estimate fuel requirements for a given flight assuming the standards and operating procedures applicable to the examined concepts. The first model is used to determine fuel requirements for a given flight on a specified route and specified flight level and speed profiles. The second one is an optimization model used to determine the optimal flight level and speed profiles for a given flight on a specified lateral route, and the corresponding fuel requirements. This model takes into consideration the track definitions, flight equipage, and differences in planning altitude profiles for the track portion of the flight (the non-equipped aircraft maintain the same flight level while on track, while the equipped ones attempt to pursue their optimal step-climb profiles throughout their flights). In addition, both models consider other main operating practices typical for the oceanic environment, such as maintaining constant Mach while cruising along the same flight level.

In general, each of the models starts with the appropriate landing weight at the destination airport determined from the aircraft type operating empty weight, estimated fuel reserves and passenger weight. Next, they calculate the amount of fuel required by integrating backwards from the destination to the airport of origin in discrete steps specified by the flown trajectory (4D). In each of the steps, the weight of the aircraft upon reaching the previously observed point is considered, as are the average airspeed and vertical profiles for the segment between the previous and current points, and the wind information relevant to that particular segment of the airspace. Simultaneously, the feasibility of each flown trajectory is investigated and any potential violations of the aircraft performance characteristics are reported. The models then calculate the amount of fuel required to complete the observed flight segment, repeating the process until each flight reaches its origin.

The fuel consumption models applied the Eurocontrol Base of Aircraft Data models (Bada version 3.3)[14], which uses a force-balance method to approximate the thrust required and uses this to compute the fuel flow. Bada provides drag polars and fuel

[14] Please refer to "Model Accuracy Report for the Base of Aircraft Data (BADA) Revision 2.5", dated December 1996, for a comprehensive validation of the methodology used to simulate the performance characteristics for the 30 aircraft models included in version 2.5; note that the BADA version 3.3 encompasses additional 41 aircraft models (total of 71).

consumption as a function of thrust for various aircraft types. Figure 3-8 shows the force-balance. Lift is obtained from the weight and climb angle. Drag is obtained using the Bada model from the required lift coefficient, Mach number and dynamic pressure. Aircraft thrust is assumed equal to the drag plus a term for rate of climb and longitudinal acceleration. The fuel flow is obtained from the thrust and altitude using the Bada models.

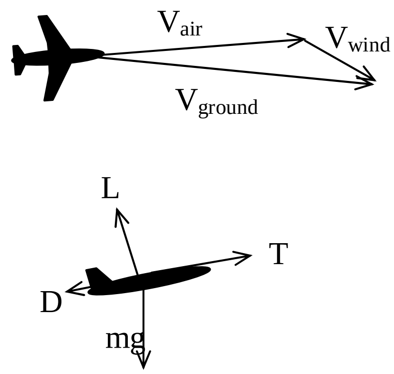

Figure 3-8 Wind vectors and force-balance

Once the fuel-flow is obtained, the specific range for a flight can be calculated using the ground speed that is obtained through vector arithmetic of the air and wind velocities. The fuel flow is typically obtained in pounds per hour. By dividing by the airspeed in knots, this provides the fuel flow in pounds required per nautical mile. The optimal altitude is that which will minimize the required pounds of fuel per nautical mile, and is a function of the winds at the different flight levels. As the flight consumes fuel, the weight of the aircraft will decrease and the optimal flight level will change.

3.6 Model for Generating Optimal Altitude Profiles

Based on the current operating practices in NATOTS and improvements enabled by ATOP, the optimal profiles for the non-equipped flights were determined by assuming constant altitudes are flown within the non-radar portion of the NATOTS (portion controlled by an oceanic air traffic controller), and step-climb profiles before and after it. On the other hand, the optimal profiles for the equipped flights were generated by assuming an ability to perform step-climbs throughout the flight, including the segments flown within the NATOTS. The model for generating the optimal altitude profiles considers winds and International Standard Atmosphere, and assumes that each flight, regardless of its equipage, maintains constant optimal air speed (Mach number) while flying along the same flight level.

The most efficient altitude profile for each of the simulated non-equipped flights was determined by examining the whole flight trajectory from origin to destination airports, and by assuming great circle trajectories between the origin airport and track system, and between the track system and destination airport. A set of 308 potential trajectories were developed by restricting the track segment of each flight to a single altitude from 28,000 to 41,000 ft (in increments of 1000ft) and by maintaining the air speed constant from 0.7 to 0.91 Mach (in increments of 0.01). The corresponding fuel requirements were then determined for each of these profiles, and the optimal profile was selected through an exhaustive search of all potential solutions as the one with the lowest total cost (aggregated cost of fuel requirements and flight duration).

The most efficient altitude profile for each of the simulated equipped flights was also determined by examining the whole flight trajectory from origin to destination airports, and by assuming great circle trajectories between the origin airport and track system, and between the track system and destination airport. In addition, it was assumed that the equipped flights planned and attempted to step-climb throughout their flight, as opposed to only outside the track system.

3.7 Oceanic Airspace Operations Modeling

Each of the previously described optimal profiles was determined independently of the nearby traffic; therefore, they represented theoretical optimums. A discrete event simulation model was then developed to “separate” the optimal profiles by incorporating the interactions between the flights. As a result, the constrained optimal profiles were created based on assuring no traffic violations under the applicable separation standards.

Whenever a flight could not follow its theoretical profile due to surrounding traffic, the model would determine its flight level as the most cost efficient available above or below the desired flight level. The model would then check periodically for availability of the preferred flight level (again, preferring the most cost efficient flight level if the optimal was not available) until it was either successful or until it reached the next profile change point. Within the track system, however, the flight level assigned at the track entry was maintained for each of the non-equipped flights until the flight exited the track system; at that point the model resumed attempting to improve the flown altitude profile for each flight flying at a sub-optimal altitude (Figure 3-9).

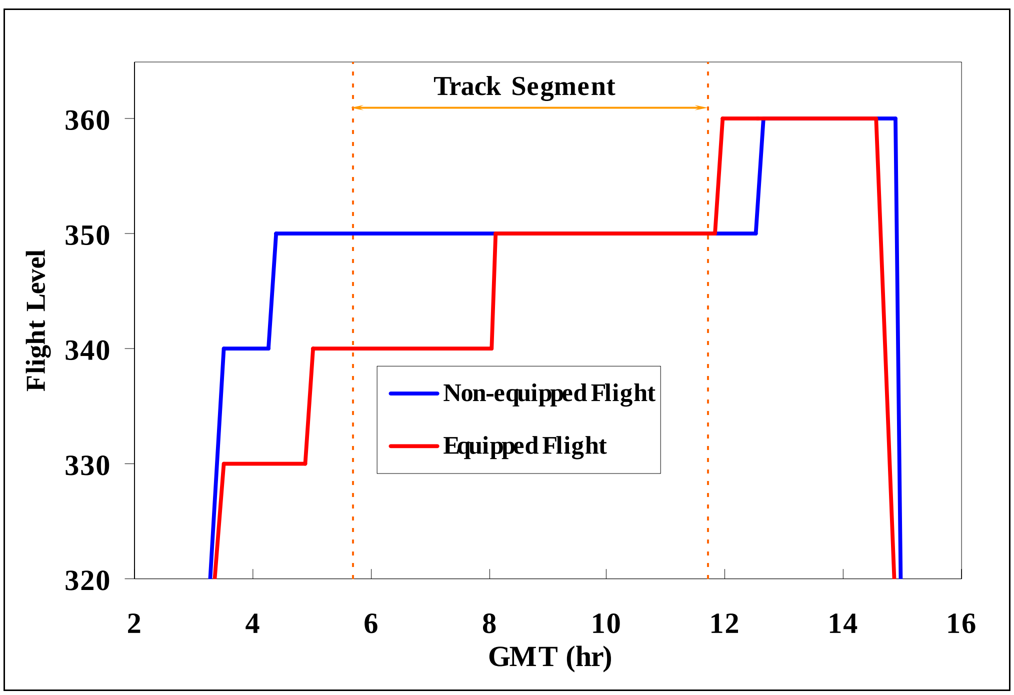

Figure 3-9 Step Climbs as a Function of Equipage

3.7.1 Simulation Scenarios

A total of 72 simulation scenarios were investigated, each consisting of a combination of the following:

- Demand level: 2005, 2010, and 2015
- Equipage level: 0, 25, 50, 75, and 100
- 2 sets of tracks: early morning eastbound (V-Z) and early afternoon westbound tracks (A-F).
- Type of track configuration:
    a) track system currently used by ATC in NAT OTS,
    b) current track system with certain tracks designated for use by equipped flights only, further referred as the segregated tracks scenarios, and
    c) track system described in b) with additional reduced separation tracks placed between the tracks designated for equipped flights, these tracks are inserted with 0.5 degrees of lateral separation.

The scenarios involving the track configuration described in a) are further referred to as the *regular tracks scenarios*, in which the flights are free to choose any of the available tracks regardless of their equipage. The scenarios involving the track configuration described in b) are further referred to as the *segregated tracks scenarios*, in which the non-equipped flights cannot fly along segregated tracks, and the equipped flights are free to choose any of the available tracks. Finally, the scenarios involving the track configuration described in c) are further referred to as the *additional segregated tracks scenarios*, in which the segregated track capacity is increased by establishing additional segregated tracks between two adjacent segregated tracks.

In addition, 9 test scenarios were created to analyze the sensitivity of benefits to the choice of segregated track; this analysis was performed only for the eastbound tracks and 25% equipage level.

4 Results

4.1.1 Characteristics of Future Traffic Demand

The main goal of this research effort was to determine the sensitivity of benefits to demand and equipage levels. Therefore, the first step involved investigating the characteristics of future demand for the NAT track system, including flight schedules and fleet mixes. Three demand levels were investigated: 2005, 2010 and 2015.

Traffic growth parameters were adopted from the Report summarizing the conclusions of the 34th North Atlantic Traffic Forecasting Group[15] (NAT TFG/34) meeting. NAT TFG/34 Report provides comprehensive information about short (2004-2010), medium (2015) and long-term (2020) forecasts of air traffic over the North Atlantic, both for total passengers and aircraft movements. In addition, the report provides air carrier fleet information, including the current fleet mix, aircraft on order and aircraft planned to retire; this information is presented by air carrier and aircraft model for years up to 2013.

4.1.1.1 Traffic Growth Parameters

NAT OTS traffic was grown using a set of actual flights performed in October 2004 as a baseline and appropriate growth parameters for the following groups of flights: scheduled (average annual growth rate of 4.50%), non-scheduled (2.68%), GA (3.7%), military (-1.95%), and cargo (4.30%).

Using the approach described in the Section 3.3, *Future Traffic Demand Modeling*, traffic demand files were generated for the years of 2005, 2010 and 2105. As compared to the baseline 2004 traffic levels, the resulting traffic counts indicate the overall growth of 7.6% by 2005, 30.4% by 2010, and 58.9% by 2015.

4.1.1.2 Air Carrier Fleet Mix

Once the future schedules were generated, the aircraft models were modified to reflect fleet mix forecasted for the future years of interest. A comparison of a sample of actual 2004 traffic data to the 2004 fleet projections from NAT TFG/34 Report revealed that the distribution of airframes in air carriers' fleets is not proportional to the distribution of aircraft models typically flown in NATOTS. To account for the corresponding preferences, a list of aircraft models was developed for each origin-destination pair in decreasing order of total trip costs (aggregated fuel and time costs were calculated using the fuel requirements model described in Section 2.1.3, Fuel Requirements). This list was then used to determine aircraft model for each of the future flights based on carrier preferences and aircraft availability. Carrier preference was determined by analyzing the total cost of flying each of the available aircraft models on the observed market, and aircraft availability was determined by considering the corresponding carrier fleet size and the typical airframe utilization for the observed market. Finally, the most efficient available aircraft model was always chosen for each of the modeled flights.

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[15] NAT TFG is one of the ICAO North Atlantic Region Groups, operating directly under its main North Atlantic Systems Planning Group (http://www.nat-pco.org/).

Aircraft types to be replaced (retired) were identified as those that had decreasing inventory in the TFG report, and the percentage decrease for each retiring type was applied to the corresponding future flight schedule. Since the year 2005 was not included in the report, it was estimated based on the trend from 2004 through 2020 and known delivery schedules for certain aircraft types.

For each aircraft type being replaced, a prioritized list of preferred replacement aircraft types was determined by selecting models that most closely matched the retiring aircraft and sorting them in order of decreasing efficiency. Replacement airframes that are more efficient were used to the maximum extent possible (as available in inventory).

Finally, the flights performed by an air carrier on the same market are matched such that the return leg is given the same airframe as the forward leg whenever matches are possible according to airport pair and necessary gate turn-around time.

Using the described method, the distribution of flights by aircraft models was determined as presented in Table 4-1.

Table 4-1 Forecasted Fleet Mix in NAT OTS

	2004	2005	2010	2015
B767	32%	33%	30%	29%
B777	19%	19%	22%	22%
A330	15%	15%	16%	17%
B747	14%	13%	12%	8%
A340	7%	8%	7%	7%
B757	3%	3%	3%	3%
MD11	2%	2%	0%	0%
DC10	1%	1%	0%	0%
GLF4	1%	1%	1%	1%
CL60/CL64	1%	1%	1%	1%
A380	0%	0%	3%	6%
B787	0%	0%	3%	5%

4.1.1.3 Equipage Considerations

Flight equipage was determined by considering the flown aircraft models and desired overall equipage levels. Five different equipage levels were considered for each of the three years: 0 (baseline), 25, 50, 75 and 100. Note that this study does not address what the equipage requirements should be, but assumes that the equipped flights are capable of reliable and accurate navigation, communications and surveillance necessary to support reduction of separations down to 30NM horizontally; the longitudinal separations from a non-equipped flight was assumed to remain 10 minutes using the Mach technique.

Aircraft models were divided into groups that are likely to be equipped in a similar timeframe. For instance, A380 and B787 are assumed to enter the service appropriately equipped, whereas B777-300, A340-500 and A340-600 were assumed to equip before

B777-200, B747-400, A340-300 and all other aircraft models. Finally, the percent of fleet considered equipped was adjusted to produce the desired overall equipage levels. The resulting percent of aircraft of a given type used to achieve the investigated overall equipage levels is presented in Table 4-2. The entries from this table should be read as follows: for all investigated demand levels, no flights on B767-300 and B767-400 were considered equipped when simulating traffic demand with 25% of overall equipage, about 25% of them were considered equipped in the scenarios with 50% overall equipage, and 75% in the scenarios with 75% overall equipage.

Table 4-2 Aircraft Equipage Considerations

	2005 Overall Equippage			2010 Overall Equippage			2015 Overall Equippage		
AC Type	25%	50%	75%	25%	50%	75%	25%	50%	75%
A330-200/300	-	50%	100%	-	50%	75%	-	50%	75%
A340-300	75%	100%	100%	50%	75%	100%	40%	60%	75%
A340-500/600	100%	100%	100%	100%	100%	100%	100%	100%	75%
A380	100%	100%	100%	100%	100%	100%	100%	100%	100%
B747-400	50%	75%	100%	50%	75%	100%	33%	70%	75%
B757-200	-	-	30%	-	-	30%	-	-	30%
B767-300/400	-	25%	75%	-	25%	75%	-	25%	75%
B777-200	75%	100%	100%	50%	75%	75%	40%	60%	75%
B777-300	75%	100%	100%	50%	100%	100%	40%	60%	100%
B7E7	100%	100%	100%	100%	100%	100%	100%	100%	100%
CL60/CL64	-	-	100%	-	-	100%	-	-	100%
F900	-	-	100%	-	-	100%	-	-	100%
GLF4	-	100%	100%	-	100%	100%	-	100%	100%

4.1.2 Regular Track Scenarios

4.1.2.1 Fuel and Time Requirements

On average, it takes about 7.12 hours to complete a flight via NATOTS[16] (from origin to destination). This average flight duration remains fairly constant for all investigated demand and equipage levels. This is because the airspace operations and fuel consumption models are designed to maintain flight times whenever possible. Scheduled flight times for each flight are adjusted only as necessary in situations when the cost of delay would exceed the cost of additional fuel requirements or when it would be aerodynamically impossible to maintain given flight duration (for instance, if the required speed would be too low or too high). Median flight duration is 7 hours, and 95% of flights are less than 9 hours long.

Average flight fuel requirements, on the other hand, are more sensitive to changes in demand than in equipage levels. However, this is a consequence of changed aircraft fleet more than a consequence of increased demand. In particular, there are more heavy airframes in service in 2015 than in 2010, and more in 2010 than in 2005. Since, it is typical for a flight in NATOTS to consume about a quarter of its take-off weight in fuel (or, about a third of its landing weight), the higher presence of heavy airframes such as

[16] The longest scheduled flight duration was 18.5hr on a flight from Newark International Airport, US, to Singapore International Airport, Singapore, and the shortest was 4.7 hr on a flight from Shannon, Ireland, to Gander (NL), Canada.

A380 will increase the average fuel requirements. This will, of course, be slightly offset by more efficient engines in future years; however, the increase in efficiency is not as significant as the increase in average weight, and the overall fuel requirements will be on average 4% higher per flight in 2010 than in 2005, and another 4% higher in 2015 than in 2010.

The average flight cost, derived by applying appropriate CI for the flown aircraft type, and composed of aggregated fuel and time cost, is illustrated in Figure 4-1. The curves clearly indicate the jump in average cost due to higher presence of heavy aircraft discussed above. In addition, it is important to point out that the slope of the average cost curves increases with demand, indicating that equipage level is more critical and that the fuel and time savings potential is higher at higher demand levels. This is because at higher demand levels there are more traffic interactions which affect the ability of flights to realize better profiles; therefore, for the same demand level, the higher the equipage level the more flights are able to improve their profiles on average. Consequently, for the same demand level, average fuel and time cost decreases with equipage level. Also, this decrease is higher for the higher demand level, which is a consequence of higher probability that the reduced separations would be applicable (due to simply more equipped flights in the system).

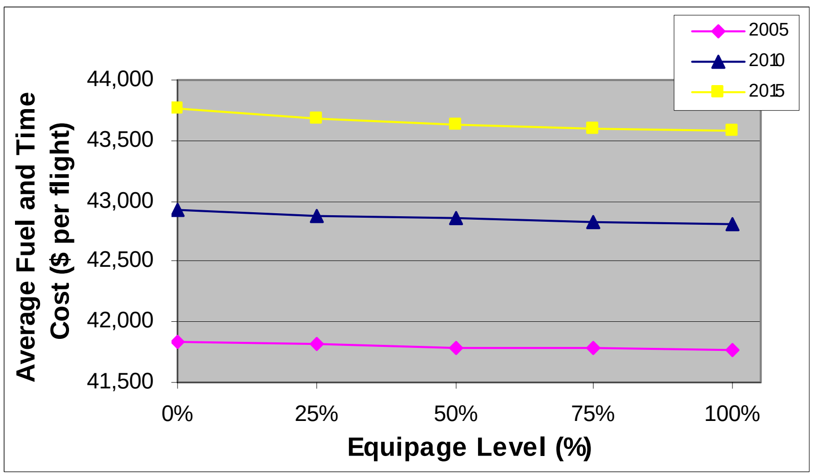

Figure 4-1 Regular Tracks: Average Fuel and Time Cost per Flight as a Function of Equipage and Demand Levels

4.1.2.2 Benefits Calculations

There are two types of benefits addressed in this research effort: (1) fuel and time savings, and (2) additional cargo revenue potential.

For a given demand and equipage levels, benefits are derived separately for each of the flights by comparing flight fuel and time requirements in the environment with the observed demand and no equipped flights to the corresponding requirements in the environment with the same demand and observed equipage level. In other words, for a given demand level, benefits represent the savings that flights would be able to realize if a given level of equipage is reached (as compared to the 0% equipage case).

Benefits calculations were performed as follows: first, for each of the flights, the corresponding fuel and time savings are determined. Then, the additional cargo potential is calculated as the difference in fuel requirements within the 0% and the observed equipage level. As discussed in Section 2.2.3, *Additional Cargo Revenue Potential*, if an operator does not have sufficient demand for additional cargo transport on a flight, the fuel savings potential would be even greater. The corresponding total annual benefits are presented separately for the cases with and without additional cargo revenue potential.

It is important to point out that a flight can realize negative benefits or penalties regardless of its equipage. This may happen if the same flight requires less fuel, for example, in a scenario with lower separations then it does in baseline scenario. Similarly, if a flight takes longer to complete in the scenario with lower horizontal separations then in the baseline scenario, it would realize negative time benefits or time penalties. Likewise, negative cargo potential represents the case in which certain amount of cargo would have to be removed from a flight in order to accommodate higher fuel requirements due to less efficient profiles.

4.1.2.2.1 Fuel and Time Savings

Average fuel and time savings statistics are summarized in Table 4-3 and illustrated in Figure 4-2. The simulation outcomes indicate that the average fuel and time cost savings increase with equipage from 0.05% to 0.18% in 2005, from 0.12% to 0.29% in 2010, and from 0.18% to 0.45% per flight; this roughly translates in per flight savings potential of $18 to $65 in 2005, $49 to $116 in 2010, and $80 to $182 in 2015.

Table 4-3 Average Fuel and Time Savings Statistics (per Flight)
(Note: negative values are presented in parenthesis)

	2005				2010				2015			
	25%	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**
Fuel and Time Savings (% per flt)	0.05%	0.11%	0.15%	0.18%	0.12%	0.19%	0.27%	0.29%	0.18%	0.30%	0.39%	0.45%
Fuel and Time Savings ($ per flt)	$ 18	$ 40	$ 55	$ 65	$ 49	$ 72	$ 106	$ 116	$ 80	$ 126	$ 160	$ 182
% Penalized	17%	27%	39%	44%	17%	26%	33%	40%	15%	26%	32%	36%
% Benefited	20%	34%	44%	53%	28%	44%	55%	58%	32%	48%	57%	63%
Avg. Penalty ($ per flt)	$ (49)	$ (41)	$ (34)	$ (33)	$ (82)	$ (62)	$ (43)	$ (40)	$ (110)	$ (67)	$ (52)	$ (41)
Avg. Benefit ($ per flt)	$ 132	$ 149	$ 154	$ 151	$ 223	$ 200	$ 220	$ 227	$ 304	$ 297	$ 307	$ 314

It is important to point out that the average fuel and time savings potential increases with both equipage and demand levels. As illustrated in Figure 4-2, for the same demand level, the average savings always increase with increased equipage. Also, for the same equipage level, the average savings always increase with increased demand as well. This is because the reduced separations are applicable more often under increased equipage and/or increased demand levels, which enables more flights to improve their profiles and creates both more frequent and higher savings.

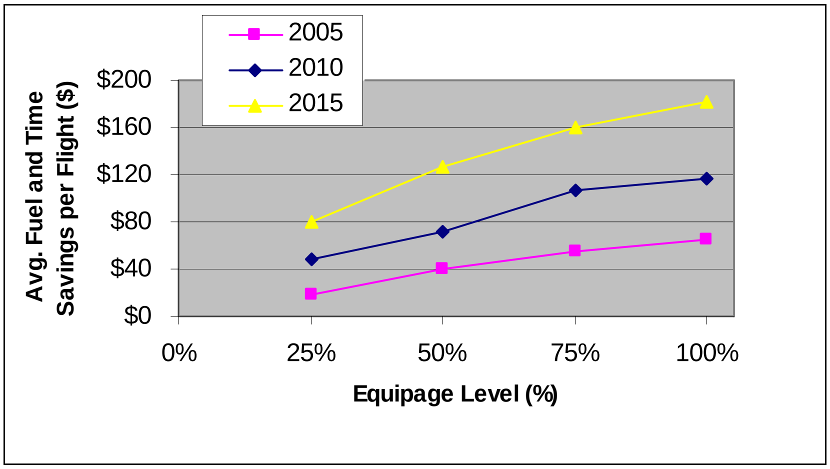

Figure 4-2 Average Fuel and Time Savings per Flight vs. Equipage and Demand Levels

Note that these saving estimates already incorporate the cost of fuel required to carry additional cargo; fuel savings potential would be about 75% higher if the additional cargo is not transported.

As illustrated in Figure 4-3, for the same demand level, the percent of flights that benefit from lower separations increase with equipage: it more than doubles from 25% to 100% equipage. This is simply because the reduced separations are applicable more often with higher equipage levels; however, due to more flights competing for still limited airspace, the percent of flights with penalties increases with equipage as well.

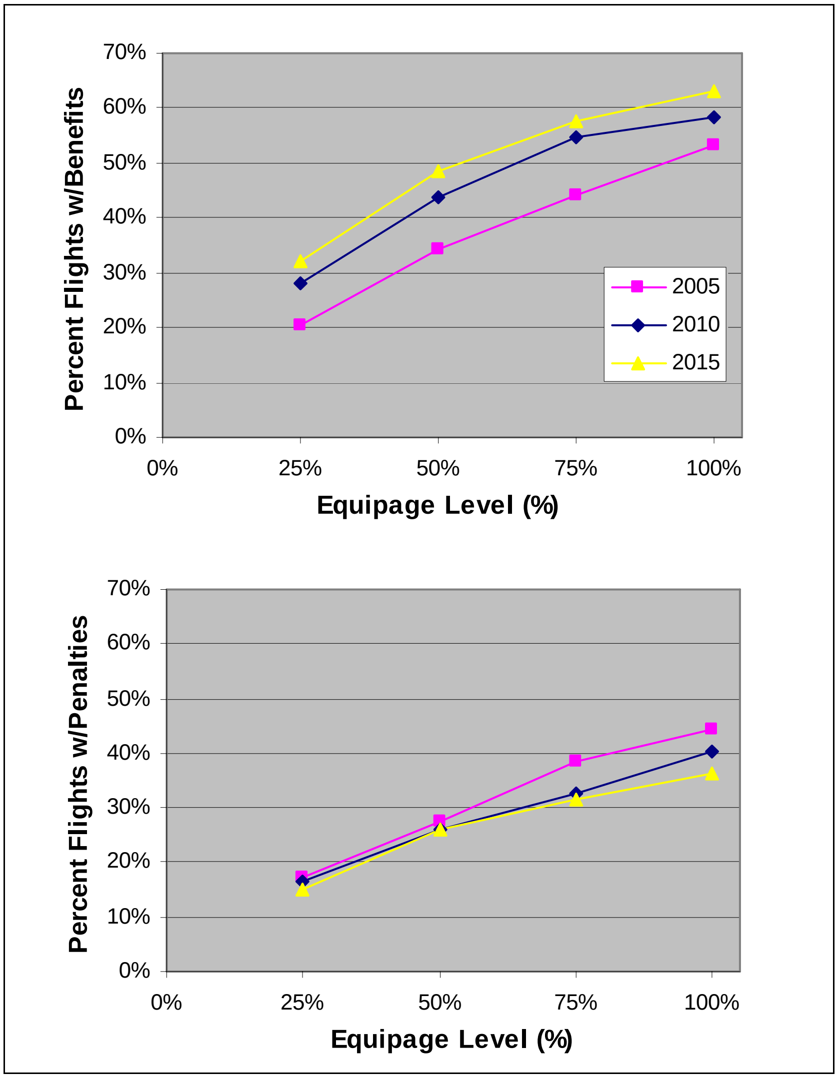

Figure 4-3 Percent of Flights with Benefits and Penalties vs. Equipage and Demand Level

Note that the percent of flights with benefits and the percent of flights with penalties do not add up to one; this is because some flights obtained the same profiles under baseline and mixed equipage scenarios. These flights, the majority of which are non-equipped, did not realize benefits or penalties, and are not accounted for in these charts. The corresponding percent of flights without any changes in fuel and time requirements is illustrated in Figure 4-4. The chart clearly indicates that this metric decreases with both equipage and demand levels; this is a result of reduced separations being applicable more often under increased equipage and/or increased demand levels, which enables more frequent changes in flown profiles. In addition, the higher the equipage level the higher the percent of flights that change behavior. Once equipped, flights are allowed to plan and perform flight level changes within the NATOTS; therefore, the percent of flights that maintain the same profile under reduced separations will decrease with increased equipage levels.

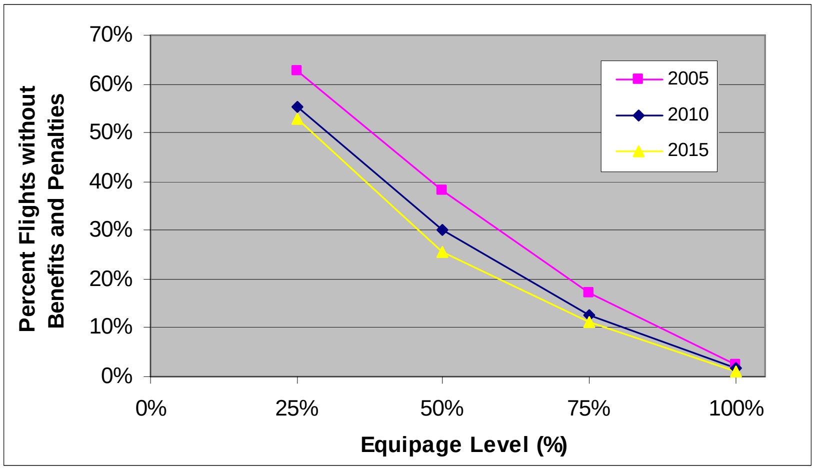

Figure 4-4 Percent of Flights with No Changes in Fuel and Time Requirements vs. Equipage and Demand Level

Of the flights that showed benefits, the average benefit per flight remains the same order of magnitude for the same demand level even with increased equipage: they oscillate around $150 in 2005, $220 in 2010 and $300 in 2105 (Figure 4-5). Once again, these orders of magnitude are driven by the fleet mix typical for each demand level and the corresponding average airframe fuel requirements and savings: the higher the presence of heavier airframes, the higher the fuel savings and the value of saved fuel. Within the same demand level, however, average benefits do not seem to be sensitive to equipage. This is because even when a flight obtains the best profile and the highest improvement in efficiency, its savings will typically be small (not more than just a few percent of average fuel requirements). Therefore, the order of magnitude of savings will *on average* remain small and more or less constant regardless of equipage level; however, the percent of flights that are capable of taking advantage of reduced separations will be significantly affected by equipage level and, thus, will impact *the overall* benefits potential (aggregated savings for all flights with benefits).

Similarly, the average penalty per flight for flights with penalties is higher with higher demand; however, it converges to the same order of magnitude for higher equipage levels. This is because with increased equipage there are more flights that can alter their profiles, if not improve, than at least to reduce the negative effect on their overall flight costs. In other words, with increased equipage, there will be more flights that experience penalties, but are still able to modify their profiles to reduce those penalties (as compared to the lower equipage rates). As a result, some flights will still be penalized simply because they cannot obtain the same profiles as they did under lower equipage levels, but the corresponding penalties will on average be smaller.

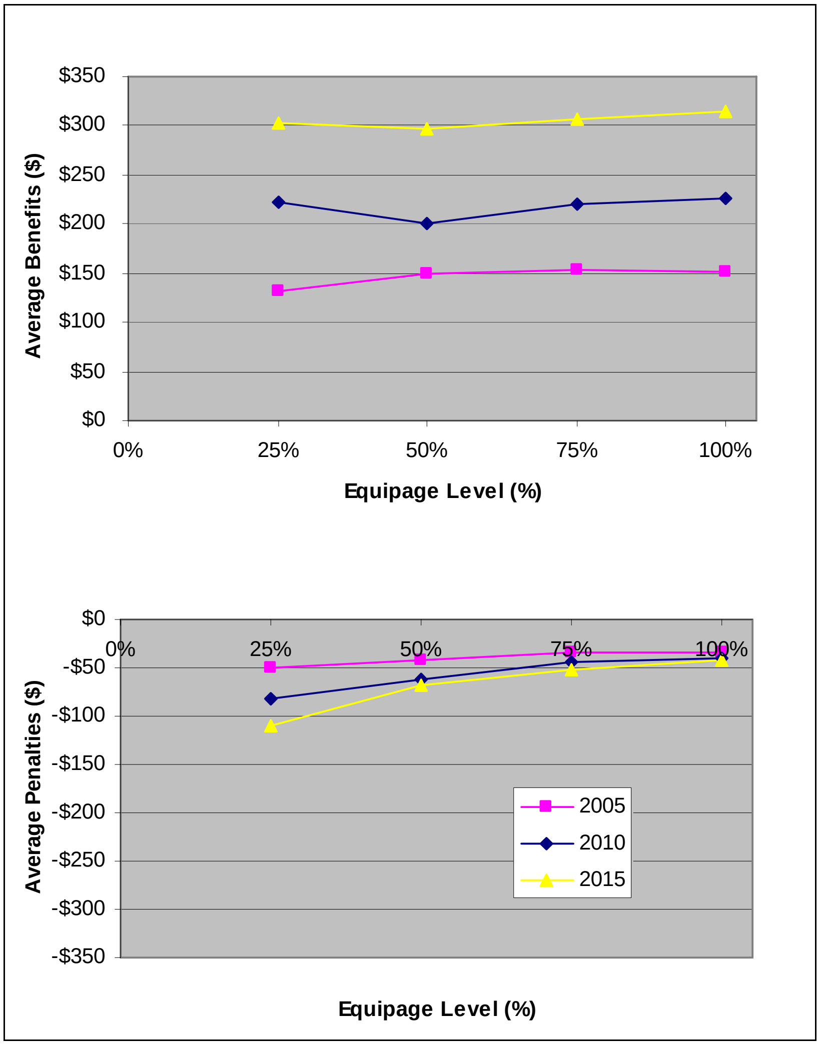

Figure 4-5 Average Benefits and Penalties per Affected Flight

4.1.2.2.1.1 Fuel and Time Savings: Equipped Flights

Finally, it is important to point out differences in distribution of benefits and penalties across equipped and non-equipped flights. As illustrated in Figure 4-6, almost none of the equipped flights obtained the same profiles after equipage and lower separations are introduced (as compared with the baseline scenarios). Percent of equipped flights with benefits slightly increases with demand due to reduced separations being more frequently applicable. However, it is not very sensitive to equipage; only at high demand levels, a slight decrease can be noticed with increased equipage. Percent of equipped flights with penalties, on the other hand, slightly decreases with demand as a consequence of reduced separations being more frequently applicable and more flights experiencing benefits.

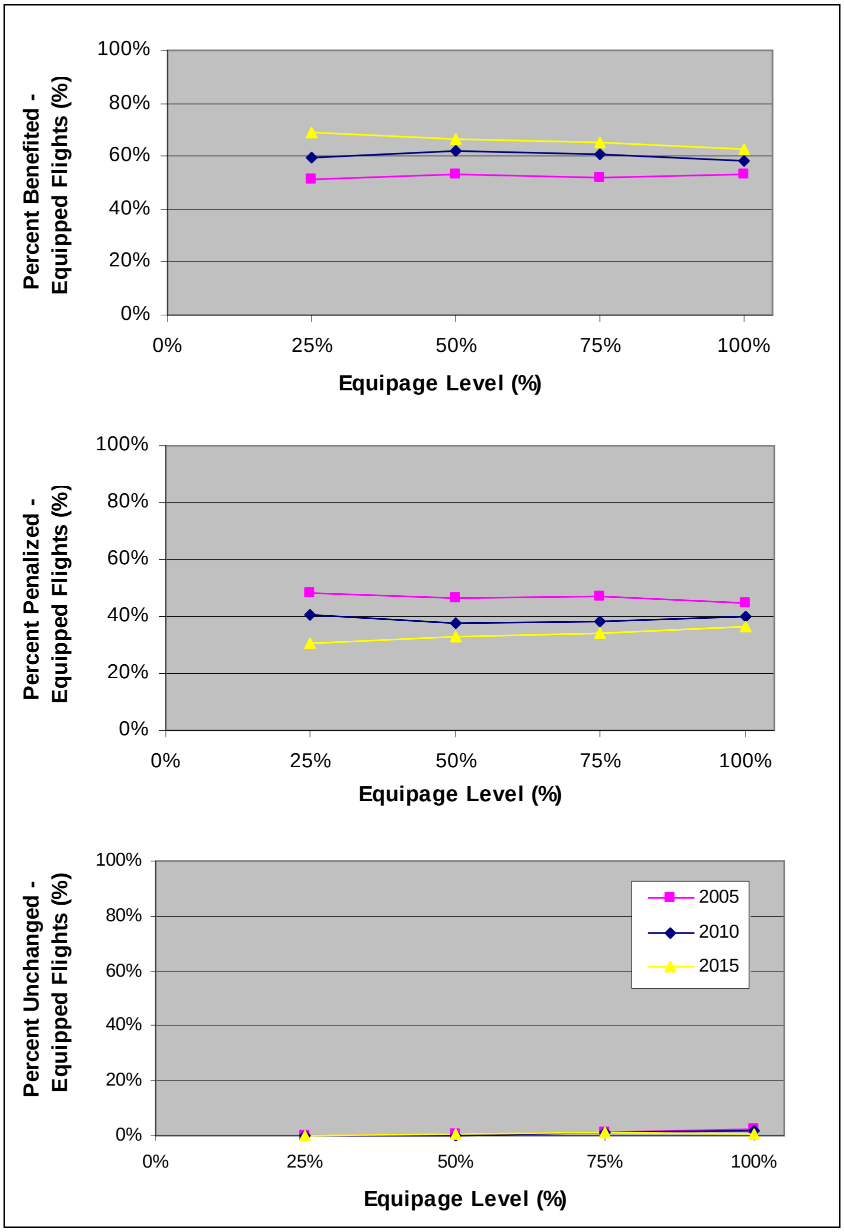

Figure 4-6 Percent Penalized and Benefited Among Equipped Flights

Most importantly, for all of the investigated demand and equipage levels, there are always more flights that benefit than are penalized. In fact, equipped flights are on average 10–20% more likely to benefit than to be penalized in the scenarios with demand level forecasted for 2005; the corresponding range for the 2010 demand level increases to 40–60%, and for 2015 to 70–170%.

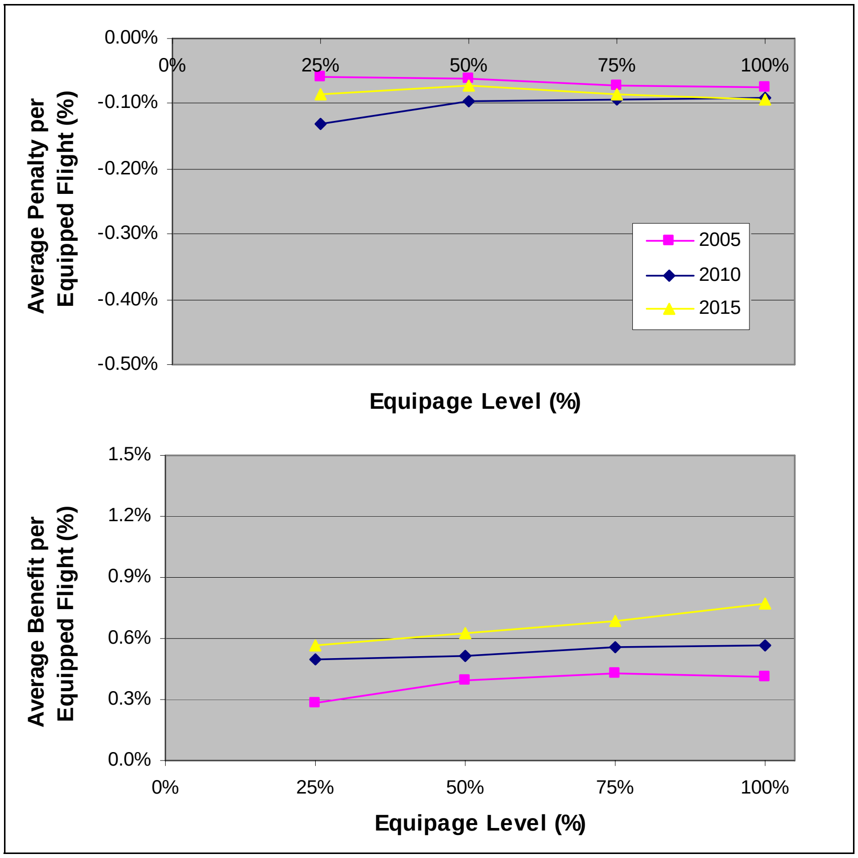

Figure 4-7 Average Penalties and Benefits for Equipped Flights

It is important to point out that the benefits and penalties per flight were calculated by using the current system as a baseline. In other words, if a flight was able to obtain better profile in the current system then in the system with reduced separations, the calculations would indicate a certain penalty. This could happen to both equipped and non-equipped flights. Operators, however, are not able to determine the benefits and penalties as precisely in the real world as it is possible in the simulated environment. This is because a given schedule can be flown only once in the real system; as a result, operators simply cannot accurately determine what the fuel consumption and flight duration on each of the flights would be if the separation standards were different. However, this is also because a schedule can be realized only once in the same environment. In other words, even if the same schedule could be flown twice with different separations standards in the real system, the flights would not be able to repeat the departure sequences and times perfectly. As a result, the distribution of flights across the system would be different, resulting in different traffic interactions and different profiles for the same flights. In addition, the winds would be different as well, which would also contribute to the differences in fuel consumption and flight duration on the same flight within the two (real) environments. Therefore, a portion of the resulting benefits and penalties would be due to the differences between the two environments and not due to the differences in separation standards, and extracting only the later would be impossible.

Finally, the fact that even some equipped flights may experience penalties should not be worrisome to the operators. As explained throughout this report, these penalties are inevitable and cannot be assessed a priory (before the flight takes off); the operator simply cannot precisely determine fuel consumption and flight duration before the flight is completed. Moreover, these occasional penalties are far exceeded by also much more frequent benefits: as illustrated in Figure 4-7, average benefits per flight that benefited were significantly higher than average penalties per flight that was penalized; that was true for all investigated demand and equipage levels. In fact, a flight with benefits saved on average from 2.7 to 7.6 times more than a penalized flight lost on average. As a result of both higher probability of benefiting and higher average benefits, equipped flights on average experience fuel and time savings of 0.12-0.18% in 2005, 0.24-0.30% in 2010 and 0.37-0.45% in 2015 (Figure 4-8).

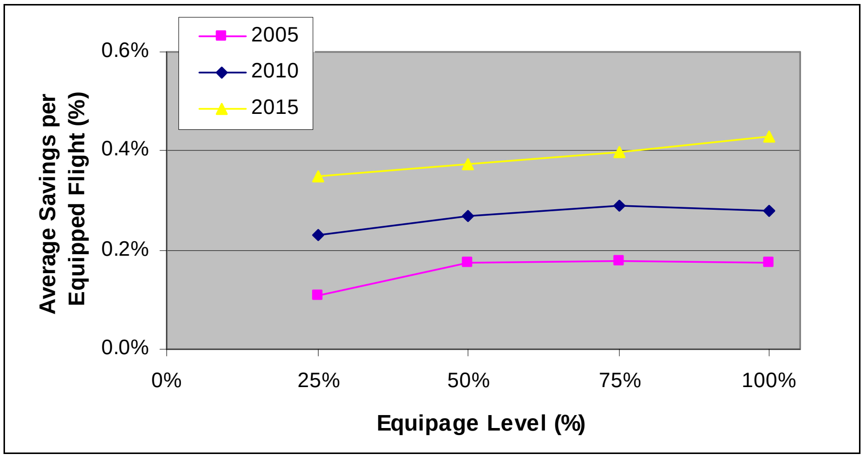

Figure 4-8 Average Fuel and Time Savings per Equipped Flights

Theoretically, an operator may decide not to use the equipment on its flight in expectation of lower costs and higher efficiencies on a particular day; however, that would be quite irrational because such outcome would not be guaranteed. In other words, even though an equipped flight may be less efficient from time to time, the "less efficient" statement is relative to the corresponding efficiency in the system in which none of the flights is equipped. As a result, gaming the system by occasionally "turning the equipment off" would only introduce another potentially detrimental effect. Operators should simply accept and absorb such occasional penalties in expectation of higher benefit potential of the equipped flights over time and over all routes clearly demonstrated by the simulations' outcomes (on average, over all equipped flights).

4.1.2.2.1.2 Fuel and Time Savings: Non-equipped Flights

Unlike the equipped flights, non-equipped flights do not experience any changes in fuel and time costs more often than they experience benefits or penalties (Figure 4-9). Percent of non-equipped flights with benefits increases with both demand and equipage; once again, this is a consequence of reduced separations being more frequently applicable and equipped flights changing their profiles and still leaving enough room for improving efficiency of non-equipped flights. However, percent of non-equipped flights with penalties also increases with both demand and equipage as a consequence of still present airspace capacity limitations, which affect non-equipped flights much more in an environment with higher density of the equipped flights.

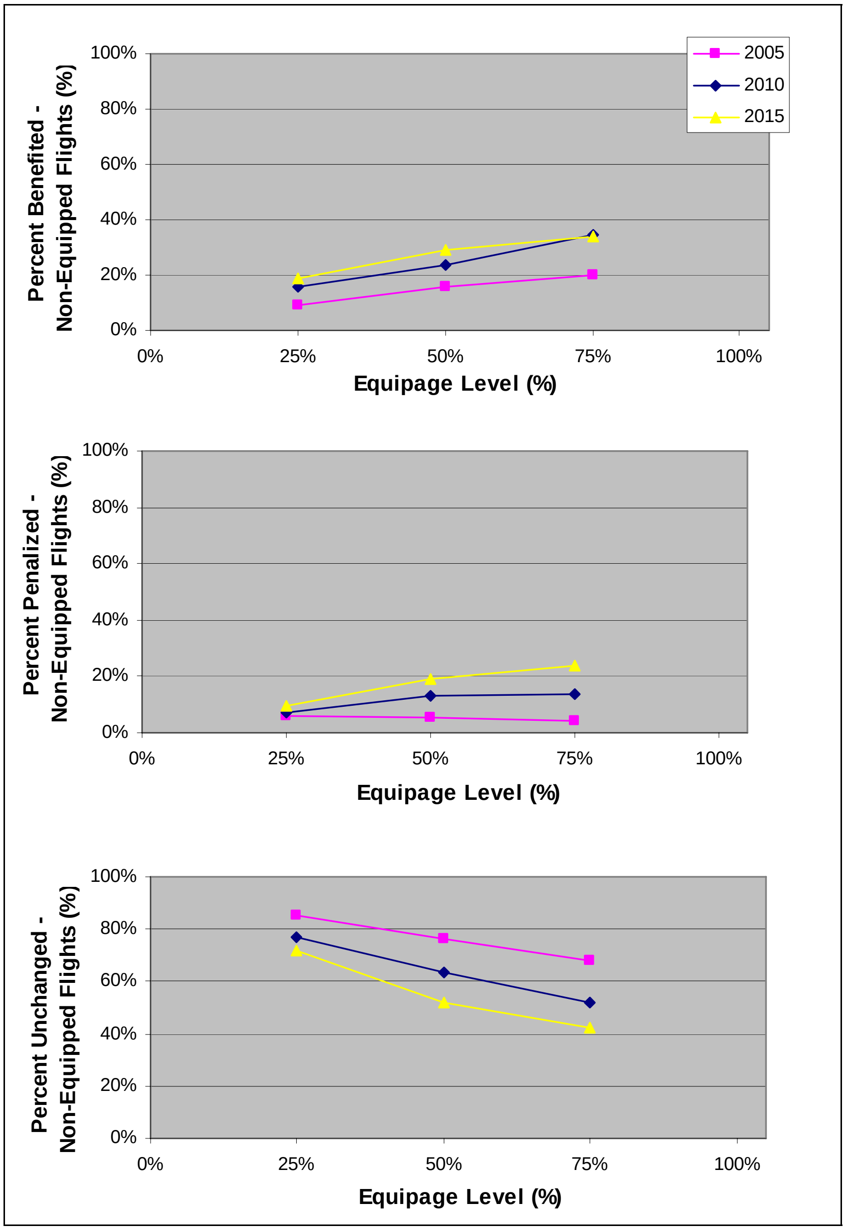

Figure 4-9 Percent Penalized and Benefited Among Non-equipped Flights

As with equipped fights, there are always more non-equipped flights that benefit than are penalized for all of the investigated demand and equipage levels. However, non-equipped flights are on average 50–149% more likely to benefit than to be penalized in the scenarios with demand level forecasted for 2005; the corresponding range for the 2010 demand level increases to 180–260%, but then starts decreasing to 140–190% for 2015; this may be an indication of a nearby tipping point that can cause benefits to revert to penalties with higher increases in demand.

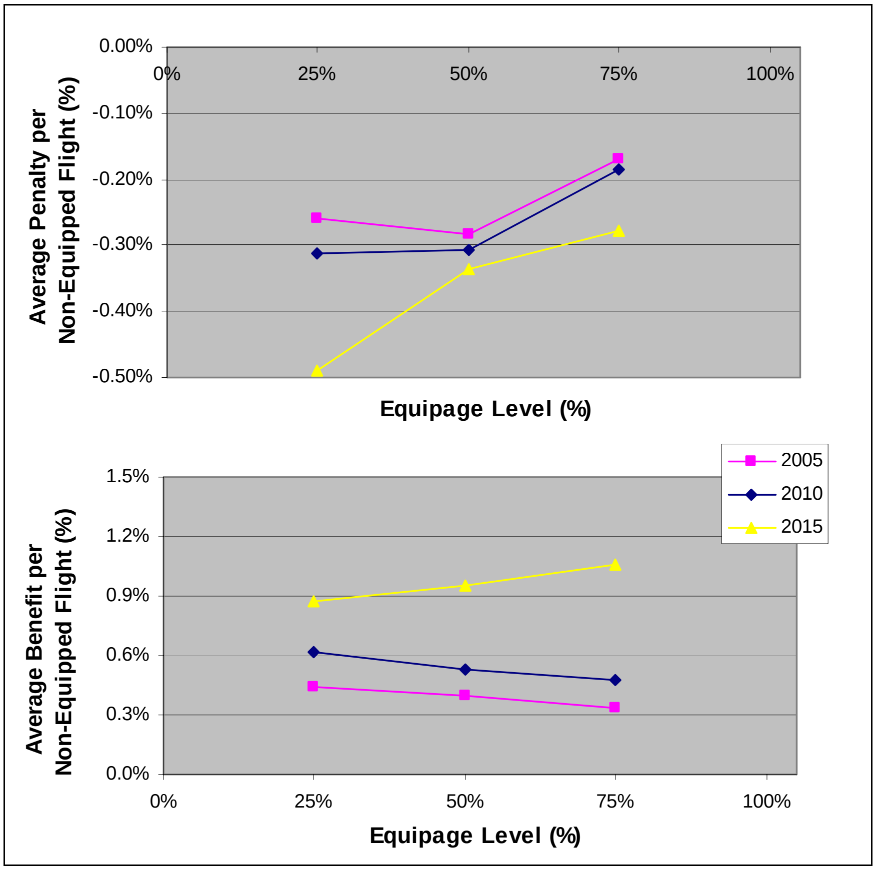

Figure 4-10 Average Penalties and Benefits for Non-equipped Flights

Finally, as with the equipped flights, average benefits per non-equipped flight that benefited were significantly higher than average penalties per flight that was penalized (Figure 4-10); that was true for all investigated demand and equipage levels. However, the corresponding ratio is much smaller for the non-equipped than it was for the equipped flights: average savings were from 1.4 to 3.8 times higher than average penalties. Overall, non-equipped flights on average also experienced fuel and time savings of 0.02-0.05% in 2005, 0.08-0.14% in 2010 and 0.12-0.295% in 2015 (Figure 4-11).

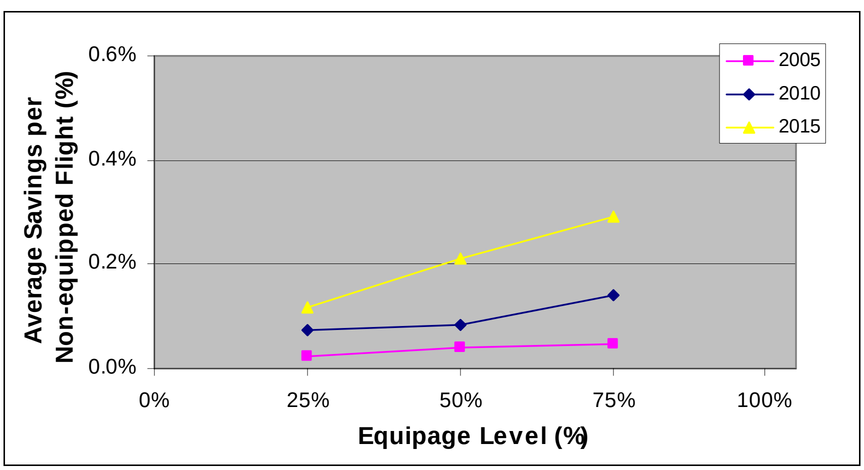

Figure 4-11 Average Fuel and Time Savings per Non-equipped Flights

Clearly, the benefits potential of the non-equipped flights is more significantly affected by equipage level with increased levels of demand.

4.1.2.2.2 Additional Cargo Potential

Since each of the flights was assumed to take-off with the maximum take-off weight, all of the fuel saved could be replaced by the additional cargo. Likewise, however, flights that experience increase in fuel requirements are assumed to remove the corresponding amount of cargo to be able to carry sufficient fuel supplies. These flights, therefore, experience penalties in cargo revenue. Table 4-4 summarizes the additional cargo potential for the investigated demand and equipage levels.

Table 4-4 Additional Cargo Potential Statistics
(Note: negative values are presented in parenthesis)

	2005				2010				2015			
	25%	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**	**25%**	**50%**	**75%**	**100%**
Cargo Penalty	$ (511)	$ (355)	$ (281)	$ (263)	$ (566)	$ (472)	$ (296)	$ (292)	$ (789)	$ (552)	$ (427)	$ (322)
Cargo Benefit	$ 819	$ 945	$ 924	$ 904	$ 1,490	$ 1,323	$ 1,411	$ 1,408	$ 2,188	$ 1,925	$ 1,982	$ 2,016
% Penalized	12%	21%	26%	30%	16%	22%	24%	28%	15%	22%	24%	26%
% Benefited	25%	41%	57%	68%	32%	53%	65%	73%	32%	53%	65%	73%
Avg. Add. Cargo Revenue (per flt.)	$ 90	$ 195	$ 284	$ 335	$ 214	$ 330	$ 514	$ 570	$ 358	$ 560	$ 742	$ 865

It is important to point out the discrepancy between the percent of flights with cargo benefits (or penalties) and the percent of flights with fuel and time benefits (penalties) (Table 4-4 and Table 4-3). This is because a change in fuel requirements for a flight directly affects its additional cargo potential, while a change in flight duration does not. More precisely, the amount of fuel needed for a flight will be affected by a change in flight duration; however, that effect was already accounted for in the calculation of the corresponding overall change in flight fuel requirements.

The simulation outcomes indicate that the additional cargo revenue potential is unevenly distributed between equipped and non-equipped flights. The percentage of equipped flights with benefits is 2–3 times higher than those with penalties, and increases with both equipage and demand. For non-equipped flights, this ratio is of the same order of magnitude at lower levels of demand (2005 and 2010), but decreases to 1.6–2.1 at the highest investigated demand. Also, benefits from additional cargo revenue potential of an equipped flight are on average up to 20% higher, but the penalties are 2–5 times lower.

As a result, depending on equipage level, equipped flights may on average benefit up to 10 times as much in additional cargo revenue than the non-equipped flights (Figure 4-12). This difference in cargo revenue potential between equipped and non-equipped flights is much higher at lower equipage levels: 2.5 times in 2005 and 2010 and 3.0 times in 2015 (25% vs. 75% equipage level). Similarly, this rate also diminishes with demand: for the same equipage level, it is about 2 times lower in 2010 than in 2005, and about 1.4 times lower in 2015 than in 2010.

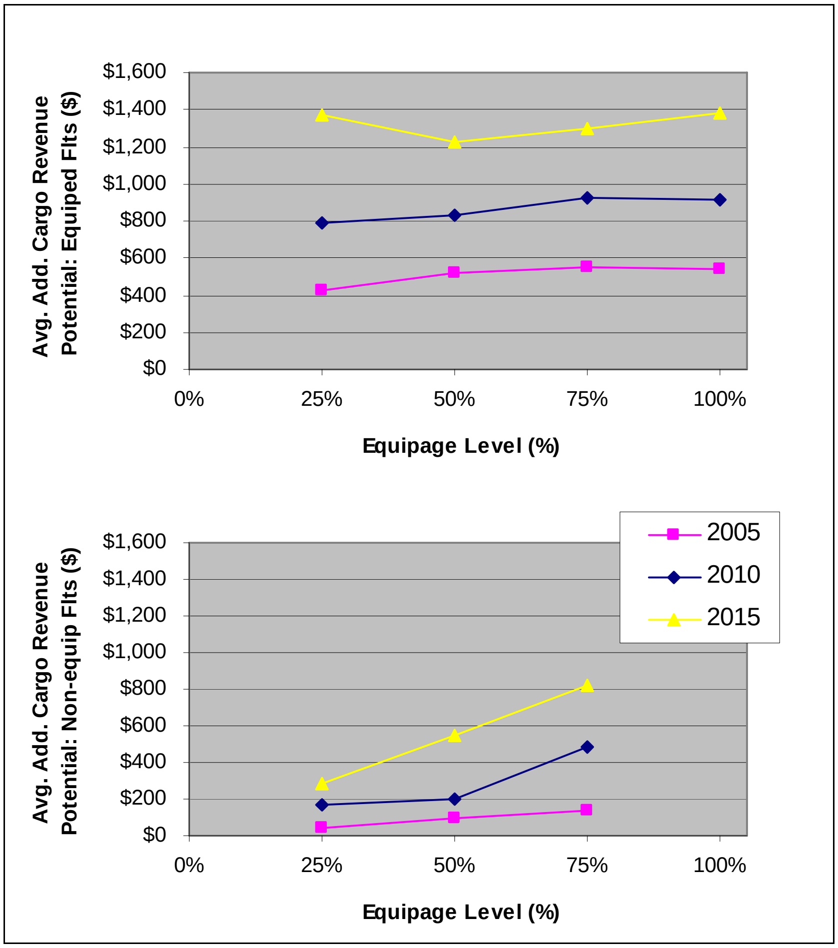

Figure 4-12 Average Additional Cargo Revenue Potential for Equipped and Non-equipped Flights

4.1.2.2.3 Total Annual Benefits

Total annual benefits were derived using current separation standards for each of the investigated demand levels as a baseline increase with both equipage and demand levels. As illustrated in It is important to point out that the additional benefits from equipping more airframes diminish with equipage. For instance, for 2005 demand forecast, operators' annual benefits will increase 2.19 times if equipage levels increases from 25% to 50%, but only 1.41 and 1.18 times higher for additional 25% increases in equipage level. In addition, for the same equipage level, increase in demand lower the marginal benefits as well. For instance, if only 25% of flights are equipped, total annual benefits in 2010 would be 3.07 times higher than in 2005, and 2.01 times higher in 2015 than in 2010. Therefore, it can be concluded that the sooner an operator equips its fleet the bigger portion of total benefits it would acquire. This, however, requires some level of equipage already established, since ability to realize benefits is directly related to density of equipped flights. In other words, a single equipped flight would not realize any benefits; if two flights were equipped, they would need to follow each other to be able to realize benefits, and only the "follower" would actually benefit. If more flights are equipped, benefits would still be realized but only if they fly in clusters. Therefore, even though it would be valuable to investigate these interactions at low levels of equipage (below 25%), it must be pointed out that benefits can be substantial regardless of equipage if the equipped flights fly in clusters. Therefore, operators need not necessarily depend upon other operators' equipage policies and decisions, but can alter their schedules to take maximum advantage by having equipped flights follow each other. Such schedule alterations would be simplified in NAT OTS, because flights are unidirectional and vast majority of them enters the track system within relatively short time period (few hours); if an operator plans its flights to fly in close proximity of each other, it would be able to realize benefits regardless of equipage availability on other flights.

Table 4-5, if future cargo demand proves sufficient to enable operators to take maximum advantage of fuel savings by substituting a portion of saved fuel weight with additional cargo, overall annual benefits will range from $36 million for the 25% equipage and 2005 demand levels to $512 million for the fully equipped operator fleet and 2015 demand forecast. If, on the other hand, operators face no additional cargo demand, they would still experience savings between $7 million and $106 million, respectively (Table 4-6).

It is important to point out that the additional benefits from equipping more airframes diminish with equipage. For instance, for 2005 demand forecast, operators' annual benefits will increase 2.19 times if equipage levels increases from 25% to 50%, but only 1.41 and 1.18 times higher for additional 25% increases in equipage level. In addition, for the same equipage level, increase in demand lower the marginal benefits as well. For instance, if only 25% of flights are equipped, total annual benefits in 2010 would be 3.07 times higher than in 2005, and 2.01 times higher in 2015 than in 2010. Therefore, it can be concluded that the sooner an operator equips its fleet the bigger portion of total benefits it would acquire. This, however, requires some level of equipage already established, since ability to realize benefits is directly related to density of equipped flights. In other words, a single equipped flight would not realize any benefits; if two flights were equipped, they would need to follow each other to be able to realize benefits, and only the "follower" would actually benefit. If more flights are equipped, benefits would still be realized but only if they fly in clusters. Therefore, even though it would be valuable to investigate these interactions at low levels of equipage (below 25%), it must be pointed out that benefits can be substantial regardless of equipage if the equipped flights fly in clusters. Therefore, operators need not necessarily depend upon other operators' equipage policies and decisions, but can alter their schedules to take maximum advantage by having equipped flights follow each other. Such schedule alterations would be simplified in NAT OTS, because flights are unidirectional and vast majority of them enters the track system within relatively short time period (few hours); if an operator plans its flights to fly in close proximity of each other, it would be able to realize benefits regardless of equipage availability on other flights.

Table 4-5 Total Operator Annual Benefits with Additional Cargo Potential

	2005				2010				2015			
	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Annual Fuel and Time Savings	$ 4 M	$ 9 M	$ 12 M	$ 14 M	$ 13 M	$ 19 M	$ 29 M	$ 31 M	$ 26 M	$ 41 M	$ 52 M	$ 60 M
Annual Add. Cargo Revenue	$ 32 M	$ 69 M	$ 101 M	$ 119 M	$ 92 M	$ 142 M	$ 222 M	$ 246 M	$ 187 M	$ 293 M	$ 388 M	$ 452 M
Total Operator Annual Benefits	$ 36 M	$ 78 M	$ 113 M	$ 133 M	$ 106 M	$ 162 M	$ 251 M	$ 277 M	$ 213 M	$ 334 M	$ 440 M	$ 512 M

Table 4-6 Total Operator Annual Benefits without Additional Cargo Potential

	2005				2010				2015			
	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Annual Fuel and Time Savings	$ 4 M	$ 9 M	$ 12 M	$ 14 M	$ 13 M	$ 19 M	$ 29 M	$ 31 M	$ 26 M	$ 41 M	$ 52 M	$ 60 M
Annual Add. Fuel Savings	$ 3 M	$ 7 M	$ 11 M	$ 12 M	$ 10 M	$ 14 M	$ 18 M	$ 19 M	$ 19 M	$ 30 M	$ 40 M	$ 47 M
Total Operator Annual Benefits	$ 7 M	$ 16 M	$ 23 M	$ 27 M	$ 23 M	$ 34 M	$ 47 M	$ 51 M	$ 46 M	$ 72 M	$ 92 M	$ 106 M

Finally, the average annual benefits per airframe were calculated by determining the minimum number of airframes required to execute the simulated schedule, and by considering typical maintenance schedules. Minimum number of airframes needed to support given schedules was determined by considering which flights in the simulated schedule could be legs of a round-trip. Two flights were considered candidates for a round-tip if they were performed by the same carrier and had matching aircraft types. In addition, the two flights were required to have opposite origin/destination airport combination; for example, a possible return leg for a flight from New York (KJFK) to London (EGLL) could only be a flight from London (EGLL) to New York (KJFK) performed by the same carrier. Finally, the arrival time of the first leg was compared to the departure time of the second leg to determine if sufficient gate service time was available between the two flights. Only if all of the described criteria were fulfilled, the two flights were assumed to be flown by the same airframe.

As illustrated in Figure 4-13, the average annual airframe benefits increase with equipage and range from $76K–$280K, $179K–$469K, and $299K–$719K for 2005, 2010 and 2015 demand level, respectively.

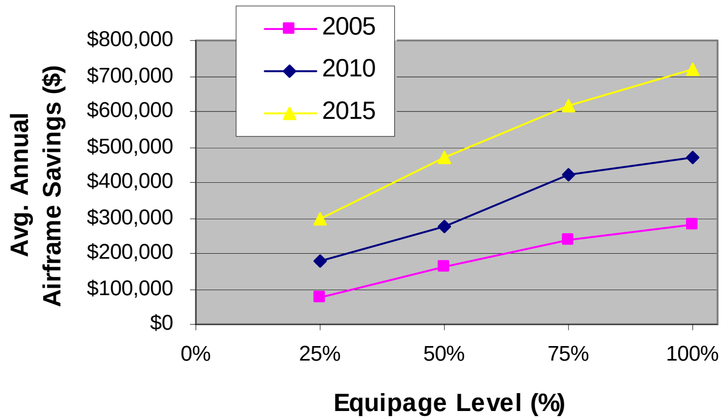

Figure 4-13 Average Annual Airframe Savings

The distribution of these benefits across equipped and non-equipped airframes is quite disproportionate: in 2005, equipped airframes save between 4 and 9 times more than non-equipped airframes, and in 2010 and 2015 2 to almost 5 times more (Figure 4-14). Note that differences in benefits potential between equipped and non-equipped airframes is the highest for lower equipage and lower demand rates.

Clearly, even if an operator decides not to equip its fleet, it would still experience savings on average under all demand and equipage levels. However, it is also clear that equipping airframes sooner rather than later would enable that operator to return its investment in a much shorter period of time by gaining higher benefits early on. In addition, of course, the operator would also be gaining benefits for a longer period of time.

Finally, it is important to point out that further dissection of benefits by aircraft model is not sensible, simply because specific airframe benefits are, in addition to their fuel flow characteristics, also affected by the flown routes and times and by the interactions with the other nearby flights. For instance, let's say the calculations suggest that the average benefits for a B777-300 airframe are $500K, and for B767-300 airframe $250K; these two numbers would not indicate that a flight typically flown on B767-300 would be able to realize twice as high benefits if it were flown by B777-300. This is because airframe benefits are simply average benefits for a given airframe model across all flights performed by that airframe model. If the model is changed on one of these flights, its fuel efficiency would change, but not its route and nearby traffic. Therefore, even though the airframe benefits by aircraft model could be easily calculated, they were considered potentially confusing and, thus, were excluded from this analysis.

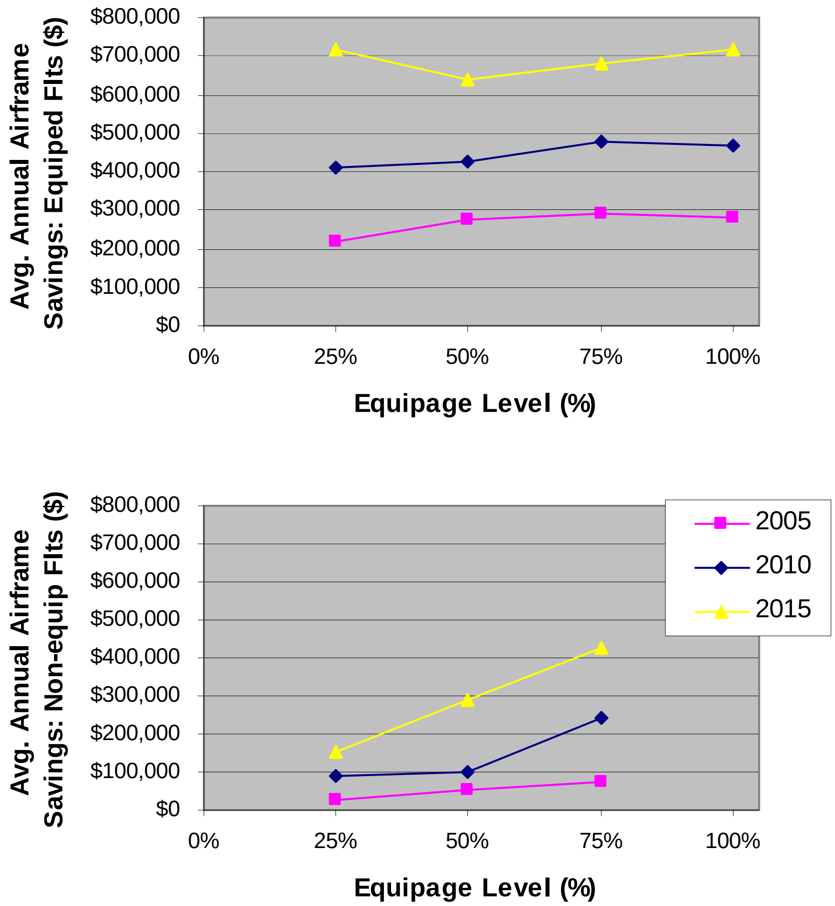

Figure 4-14 Average Annual Airframe Benefits for Equipped and Non-equipped Airframes

4.1.3 Segregated and Additional Segregated Tracks

The choice of segregated tracks was based on the preferences of the majority of the equipped flights, and preferences were established by determining the lowest cost track for each of the equipped flights. With this approach, only the optimal choice for each of the equipped flights was considered, not the traffic interactions.

The number of segregated tracks was determined by equipage level: one for 25%, two for 50% and three for 75% equipage level, respectively. Note that 0% and 100% equipage scenarios were identical to the corresponding regular tracks scenarios with the same equipage levels; this is because scenarios with 0% and 100% equipped flights require no segregation of operations based on equipage: all are either non-equipped or equipped, respectively.

Additional segregated tracks can be introduced only between two adjacent segregated tracks. Therefore, the choice of tracks assumed not accessible to the non-equipped flights may vary between the segregated and additional segregated tracks scenarios with the same equipage level. This is only when the tracks chosen as segregated in 50% or 75%

equipage scenarios were not adjacent. In these cases, the selection of segregated tracks was adjusted to allow for establishing additional track(s) at reduced lateral separations of 0.5°. Finally, the only candidates for segregated tracks were the inside tracks: B–E for westbound traffic and W–Y for eastbound traffic. All other assumptions were the same as those used for the corresponding regular tracks scenarios.

4.1.3.1 Fuel and Time Requirements and Benefits

Fuel and Time requirements in segregated and additional segregated track scenarios are the same order of magnitude as compared with the corresponding requirements in the regular tracks scenarios (Figure 4-15). Unexpectedly, however, the simulation outcomes indicate that it is slightly cheaper on average to traverse the track system with mixed operations on each of the tracks than with operations segregated according to available equipage.

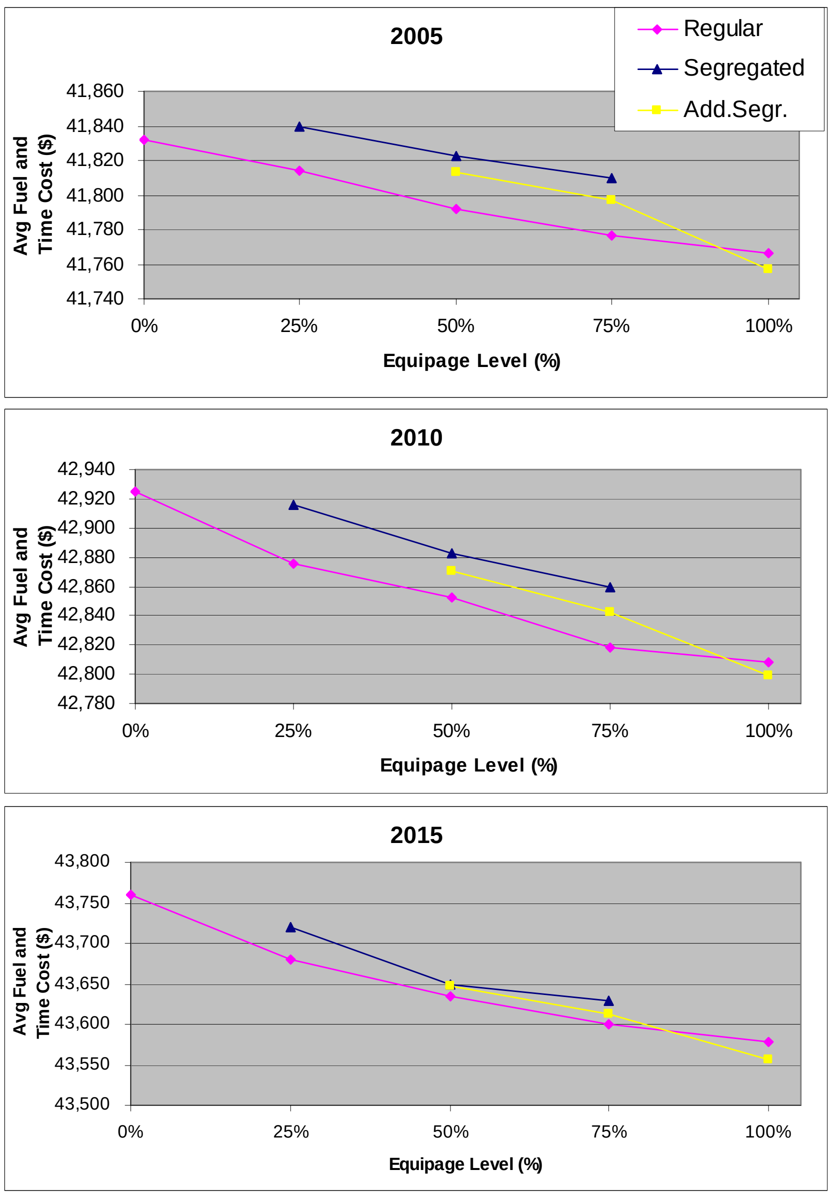

Figure 4-15 Average Fuel and Time Cost per Flight as a Function of Track Configuration, Equipage and Demand Levels

Closer examination of these outcomes reveled that this is a consequence of often high penalties to especially non-equipped flights (Figure 4-16). Even some equipped flights realize fuel and time penalties of 0.1%–0.2% (average across all penalized equipped flights). In addition, up to 50% of all flights experience penalties in some of the scenarios. As a result, segregating operations based on equipage seems like a step backwards as compared to the mixed operations throughout the track system.

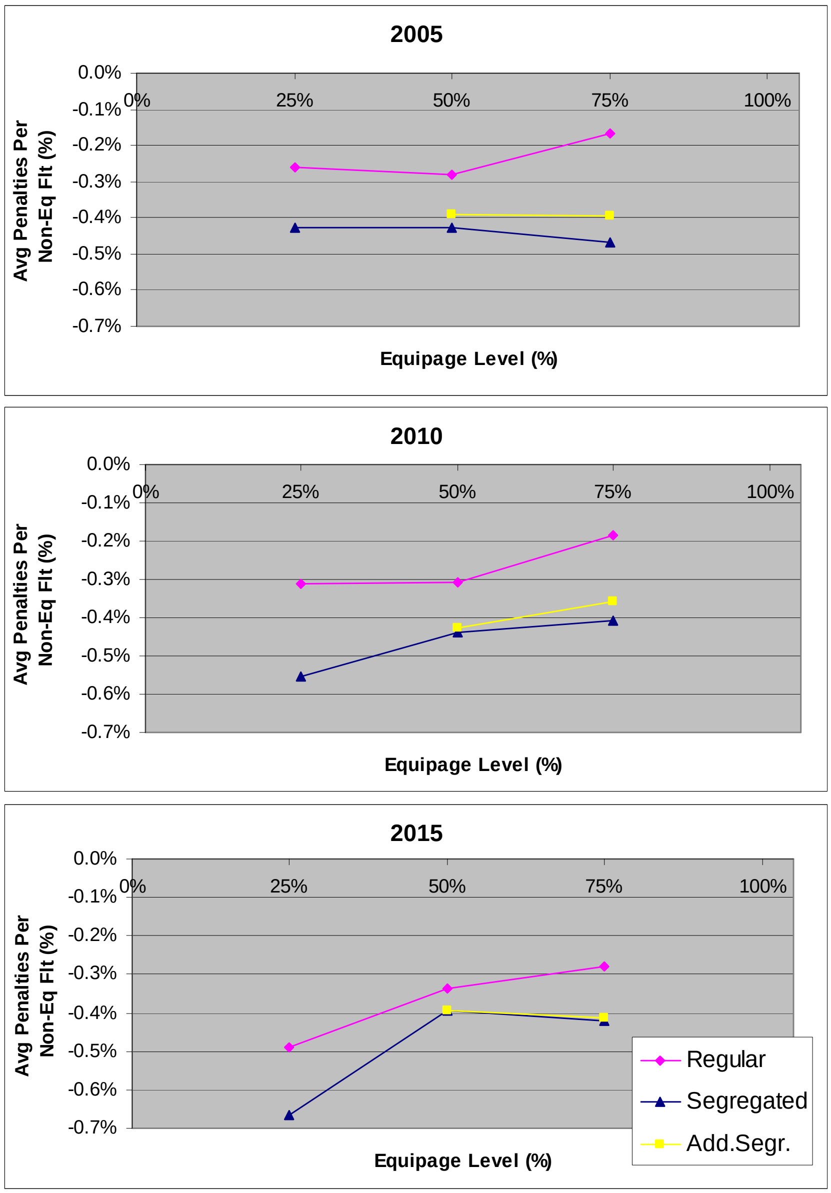

Figure 4-16 Average Penalties per Non-equipped Flight as a Function of Track Configuration, Equipage and Demand Levels

This, however, is not a valid conclusion. More precisely, it is valid for the given assumptions, but should not be blindly accepted. In fact, these results are a consequence of the redistribution of flights based on the choice of segregated tracks. In other words, for different set of segregated tracks, flights would simply find different optimal routes and profiles based on what tracks they are allowed to fly, which would cause these outcomes to be different. In fact, whether these outcomes would be improved or not with different selection of segregated tracks is not easy, if at all possible, to determine without actually performing another complete set of simulations.

But, before we investigate the sensitivity of outcomes to the selection of segregated tracks (Section 4.1.3.2, Sensitivity of Benefits to the Segregated Track Selection), let us point out few important points for this set of simulations with segregated tracks and present the corresponding savings potential.

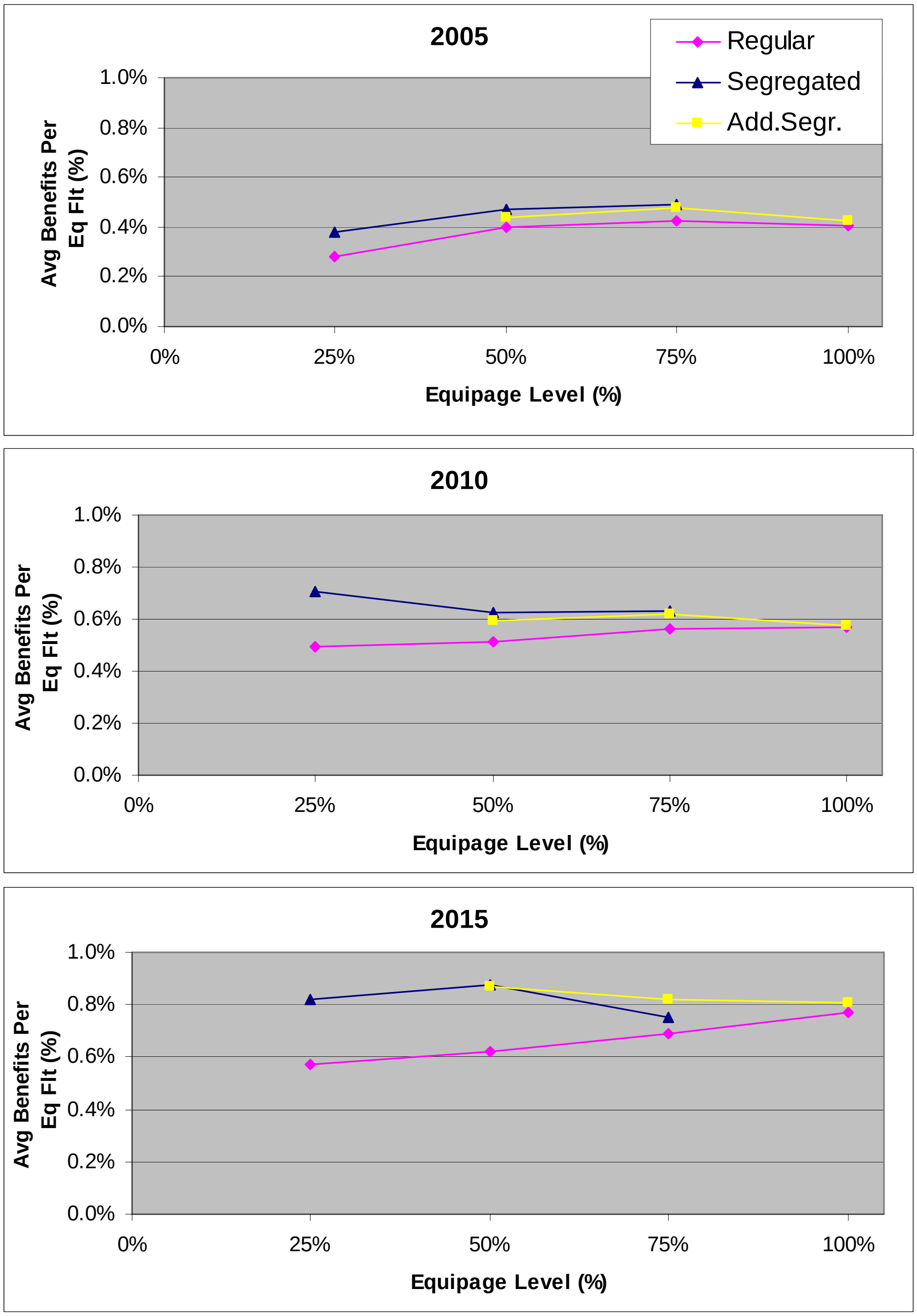

Figure 4-17 Average Fuel and Time Benefits per Equipped Flight vs. Track Configuration, Equipage and Demand Level

First, equipped flights that benefit realize higher fuel and time savings on average when operations are segregated based on equipage than mixed throughout the track system (Figure 4-17). Interestingly, having additional segregated tracks in some cases reduced the average benefits for these flights. Both of these conclusions are a consequence of flight preferences being different for different track configurations: once segregated (and new segregated) tracks are introduced, new optimal routes and profiles will be generated for *each* flight. Since segregated tracks are determined based on preferences of equipped flights alone, and do not consider traffic interaction, even the equipped flights may experience penalties if they happen to prefer the same track and attempt to enter it within the same period of time as some other equipped flight; in such instances, equipped flight swill be penalized for such greedy behavior. Since the distribution of preferences will be different for different track configurations, it can easily happen that even though capacity is higher, equipped flights cluster simply too close to each other on the same routes. In addition, since in order to introduce additional segregated track it is sometimes necessary to change the originally selected segregated tracks into the adjacent tracks, some flights will be disproportionately penalized. Such decision, however, will affect both equipped and non-equipped flights, since any change in track configuration will cause a change in preferred routing of all flights. Therefore, the decision about which track to choose as accessible to only equipped flights must be made by considering both preferences and traffic interactions of all flights.

Second, even when the segregated tracks are not selected by considering preferences and traffic interactions of all flights, flights are typically better off on average than they are in the system with current separation standards. In other words, as illustrated in Figure 4-18[17], with exception of the scenario with 25% equipage and 2005 demand levels, flights were on average experiencing savings over the baseline. However, as discussed above, this conclusion may not be valid for all other combinations of segregated tracks.

Finally, the marginal improvement in savings from higher capacity introduced by the additional segregated tracks is visible in the 100% equipage scenarios: the average benefits are higher in the additional segregated than in regular tracks scenarios for all demand levels. Note that the marginal improvement in average savings is quite small, indicating that even for the 2015 forecasted traffic, demand will still not be high enough to necessitate capacity improvements in addition to reduced separations. However, if all flights are equipped, lowering the lateral separations between tracks will not require complex regulatory amendments if lateral separations of 30 NM along the whole track are assured (especially in points in which track changes heading).

[17] Note that the average savings presented in this figure already incorporate the cost of fuel required to transport maximum amount of additional cargo weight

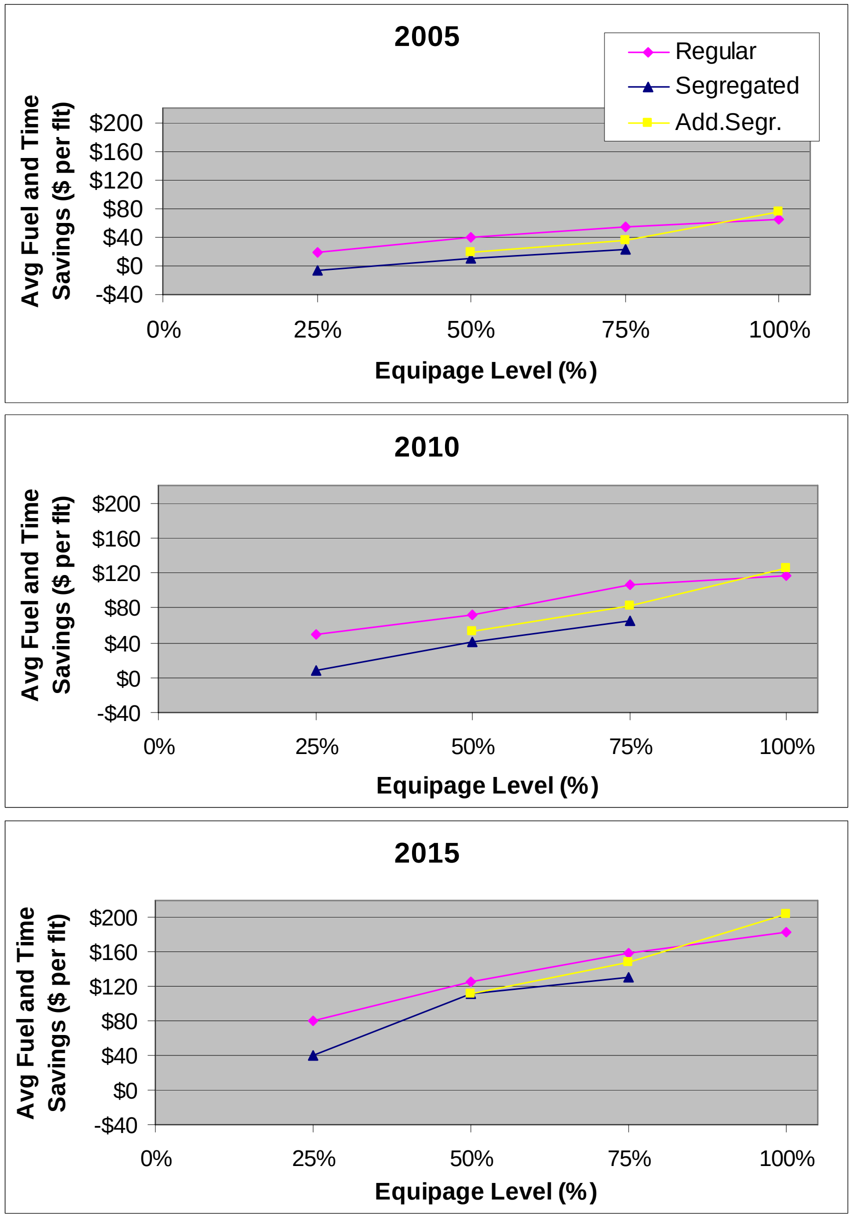

Figure 4-18 Average Fuel and Time Benefits per Flight vs. Track Configuration, Equipage and Demand Level

4.1.3.2 Sensitivity of Benefits to the Segregated Track Selection

There are several different methods that can be used to select a segregated track for an expected traffic, forecasted weather and established track system. In this study, it was assumed that segregated tracks were selected based on the preferences of the majority of the equipped flights, and the preferences were established by determining the lowest cost track for each of the equipped flights. In other words, traffic interactions were not considered, but only the optimal choice for each of the equipped flights.

However, this method did not consider the non-equipped flights at all. As a result, the equipped flights did realize savings, but the non-equipped flights were disproportionately penalized. Traffic interactions were not considered either, which created additional room for high penalties for some equipped flights as well due to inability to obtain the preferred flight level on the most preferred track. In fact, for the 2005 demand forecast and 25% equipage level, the average savings per flight were negative.

As a result, additional 9 test scenarios were created to analyze the sensitivity of fuel and time savings on the choice of segregated track: early morning eastbound traffic and 25% equipage level were investigated; since the outside tracks cannot be segregated, three sets of simulations were run for each of the three demand levels assuming tracks W, X or Y were not accessible to the non-equipped flights, respectively

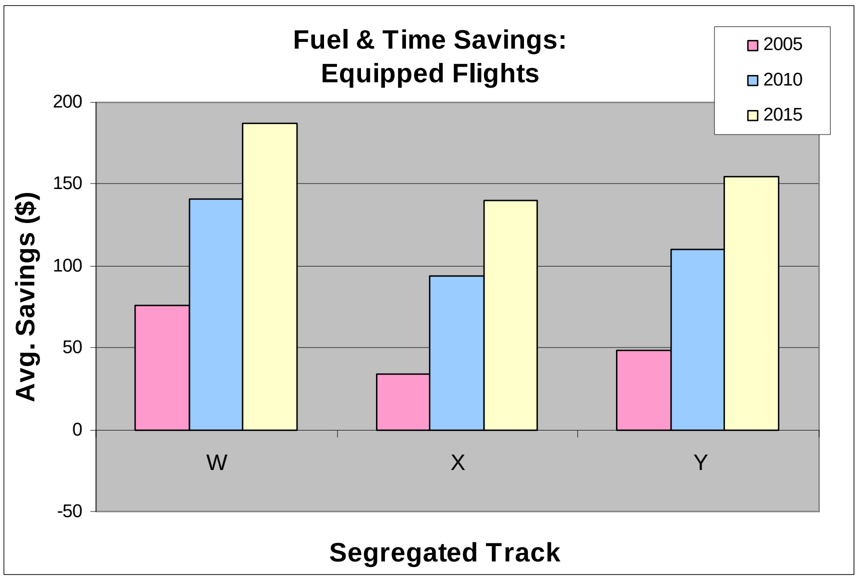

Figure 4-19 Average Fuel and Time Savings for Equipped Flights as a Function of Segregated Track Selection

As illustrated in Figure 4-19, even though track W is the best choice for all three demand levels, equipped flights will on average realize savings regardless of the choice for segregated track. However, average savings per flights (i.e., including both equipped and non-equipped flights) are not always positive. In fact, as illustrated in Figure 4-20, only if track W is selected as segregated flights will on average realize benefits for each of the three demand levels.

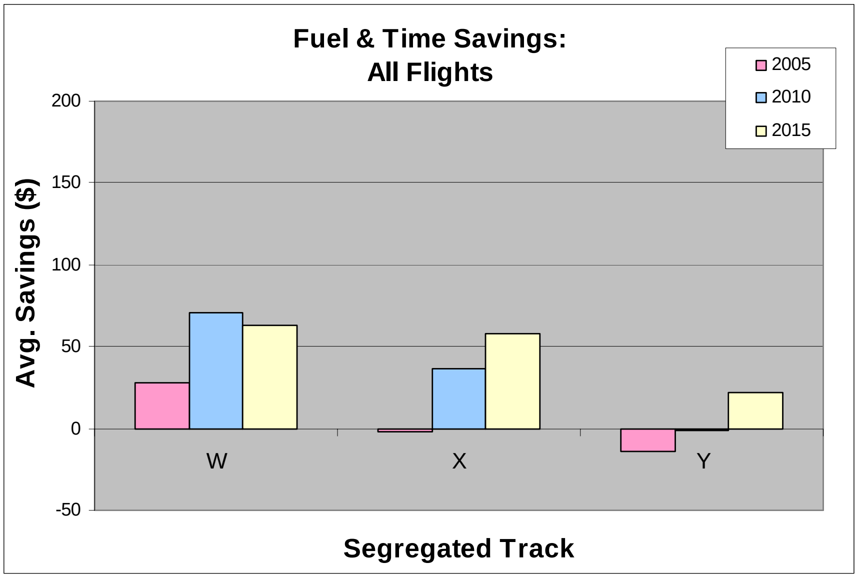

Figure 4-20 Average Fuel and Time Savings for All Flights as a Function of Segregated Track Selection

Note that the method for segregated track selection used in this research produced clearly the worst choice: track Y. Consequently, the average savings in the 25% equipage scenarios ended up being penalties instead of benefits.

In addition, note that equipped flights were capable of saving $47 on average in 2005, $109 in 2010 and $185 in 2015 with mixed operations on each of the tracks. Once again, only if track W was allocated for use of only equipped flights, permitting segregated operations based on equipage would produce higher average savings for all flights: $76 in 2005, $141 in 2010 and $186 in 2015. Note that the marginal benefits from segregating operations based on equipage diminish with demand, resulting in average savings per flight being almost identical at the highest investigated equipage level.

Based on the limited information obtained from these 9 test scenarios, it can be concluded that segregating operations based on equipage has significant potential of increasing average benefits as compared to the mixed operations on each track; this is especially true for lower demand levels. However, the method used for selection of segregated tracks needs further and careful examination.

4.1.3.3 Benefits Summary

It is important to point out that, with the exception of results from scenarios assuming 100% equipage level, the presented benefits should be treated as conservative; as demonstrated in previous section, the results from segregated and additional segregated tracks can be improved by improving the method used to select which tracks are not allowed for use by the non-equipped flights. If, on the other hand, all flights are equipped, there would be no ambiguity in segregated track selection: all of the tracks would be segregated and additional tracks established only between inside tracks.

As with mixed operations on each of the tracks, segregating operations based on equipage under reduced separations enables flight efficiency improvements. Total annual benefits derived using current separation standards for each of the investigated demand levels as a baseline increase with both equipage and demand levels. As illustrated in Table 4-7, if operators face sufficient cargo demand in the future, the overall annual benefits may range as high as from $8 million for the 25% equipage and 2005 demand levels to $512 million for the fully equipped operator fleet and 2015 demand forecast. If, on the other hand, operators face no additional cargo demand in future years, they would be able to realize even higher fuel cost savings and would overall save between $2 million and $106 million, respectively (Table 4-8).

Table 4-7 Segregated Tracks: Total Operator Annual Benefits with Additional Cargo Potential

	2005				2010				2015			
	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Annual Fuel and Time Savings	$ (2)M	$ 2 M	$ 5 M	$ 14 M	$ 2 M	$ 11 M	$ 17 M	$ 31 M	$ 13 M	$ 36 M	$ 43 M	$ 60 M
Annual Add. Cargo Revenue	$ 9 M	$ 60 M	$ 86 M	$ 119 M	$ 43 M	$ 135 M	$ 188 M	$ 246 M	$ 126 M	$ 317 M	$ 370 M	$ 452 M
Total Operator Annual Benefits	$ 8 M	$ 62 M	$ 91 M	$ 133 M	$ 45 M	$ 146 M	$ 205 M	$ 277 M	$ 139 M	$ 353 M	$ 413 M	$ 512 M

Table 4-8 Segregated Tracks: Total Operator Annual Benefits without Additional Cargo Potential

	2005				2010				2015			
	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Annual Fuel and Time Savings	$ (2)M	$ 2 M	$ 5 M	$ 14 M	$ 2 M	$ 11 M	$ 17 M	$ 31 M	$ 13 M	$ 36 M	$ 43 M	$ 60 M
Annual Add. Fuel Savings	$ 3 M	$ 7 M	$ 11 M	$ 12 M	$ 10 M	$ 14 M	$ 18 M	$ 19 M	$ 19 M	$ 30 M	$ 40 M	$ 47 M
Total Operator Annual Benefits	$ 2 M	$ 9 M	$ 16 M	$ 27 M	$ 12 M	$ 26 M	$ 36 M	$ 51 M	$ 32 M	$ 67 M	$ 83 M	$ 106 M

Introducing additional segregated tracks between the adjacent segregated tracks would enable even higher benefits: from $71M to $569M with, and from $12M to $113M, without additional cargo potential, respectively. Note that the marginal benefits from such capacity improvements are on average 10%, and decrease with demand. This is a clear indication of traffic density significantly limiting the magnitude of benefits: at lower demand and equipage levels, equipped flight can spread across airspace exclusively reserved for their use, while other flights also benefit because of less competition on tracks they can fly. With increased demand or equipage, however, the distribution of flights across the track system will change and the increased competition will cause decrease in marginal benefits. In addition, the group of flight that remains unequipped will be forced onto less efficient non-segregated tracks, and the increase in their penalties will negatively impact the marginal benefits even after introduction of new segregated tracks.

Table 4-9 Additional Segregated Tracks: Total Operator Annual Benefits with Additional Cargo Potential

	2005			2010			2015		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Annual Fuel and Time Savings	$ 4 M	$ 8 M	$ 17 M	$ 14 M	$ 22 M	$ 34 M	$ 37 M	$ 48 M	$ 67 M
Annual Add. Cargo Revenue	$ 66 M	$ 97 M	$ 134 M	$ 145 M	$ 211 M	$ 266 M	$ 317 M	$ 410 M	$ 502 M
Total Operator Annual Benefits	$ 71 M	$ 105 M	$ 151 M	$ 160 M	$ 233 M	$ 300 M	$ 354 M	$ 459 M	$ 569 M

Table 4-10 Additional Segregated Tracks: Total Operator Annual Benefits without Additional Cargo Potential

	2005			2010			2015		
	50%	75%	100%	50%	75%	100%	50%	75%	100%
Annual Fuel and Time Savings	$ 4 M	$ 8 M	$ 17 M	$ 14 M	$ 22 M	$ 34 M	$ 37 M	$ 48 M	$ 67 M
Annual Add. Fuel Savings	$ 7 M	$ 11 M	$ 12 M	$ 14 M	$ 18 M	$ 19 M	$ 30 M	$ 40 M	$ 47 M
Total Operator Annual Benefits	$ 12 M	$ 18 M	$ 29 M	$ 29 M	$ 40 M	$ 53 M	$ 67 M	$ 88 M	$ 113 M

Finally, simulation outcomes indicate that airframe benefits can on average reach of $317K, $508K and $799K for 2005, 2010, and 2015 demand levels, respectively; these figures were generated for 100% equipage levels and additional tracks established at lateral track separations of 0.5 degrees.

4.1.4 System Performance Improvement

As discussed in Section 2, Benefit Mechanisms, reduction of separation standards enables an increase in airspace capacity of the most favorable routings, which facilitates improvements in flight efficiency through the allocation of optimal or closer-to-optimal lateral routes, flight levels, and speed profiles. As a result, system performance improvement is enabled, including the accommodation of user-preferred routes and improvement in responsiveness to in-flight requests such as altitude change requests.

It is important to point out that the measurements observed in this research effort pertain to the modeled system and are not equivalent to the corresponding measurements collected in the real system. For instance, all measurements were collected at precise moments when a change in preferences occurs in the modeled environment, while the real system operates with lower accuracy and higher latency. Therefore, the numbers presented in the following charts should not be directly compared to the corresponding metrics collected by the FAA Offshore and Oceanic Directorate. The results should only be used as indicators of the relative improvements in system performance; for instance, for the 2005 demand level, an improvement in altitude change requests granted of 0.74% can be expected if the equipage levels increase from 0% to 25%.

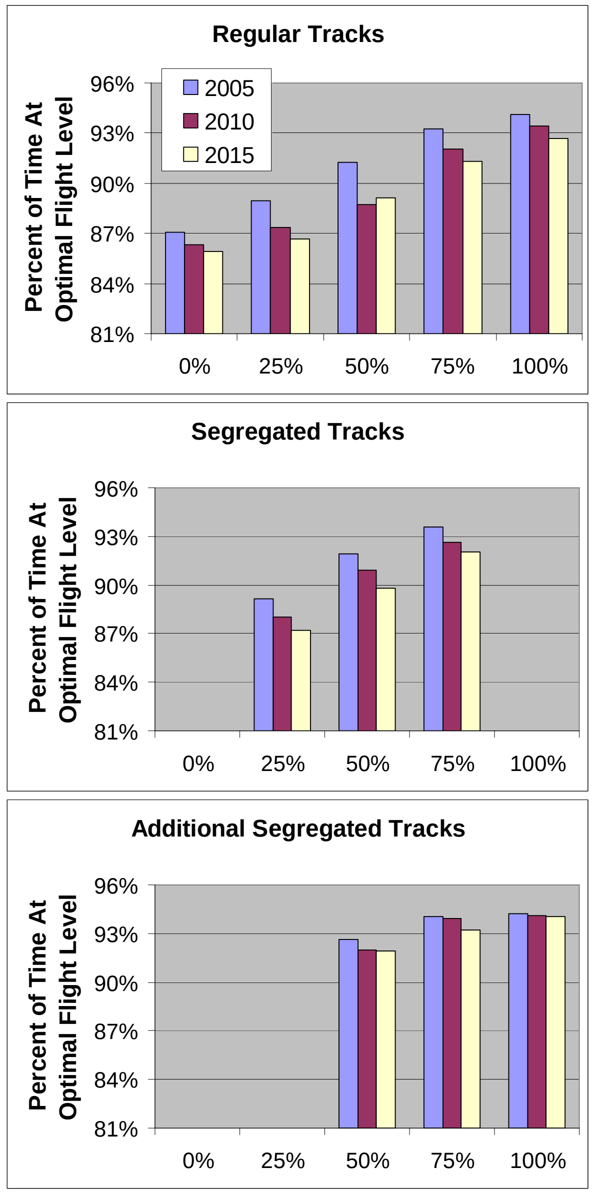

Figure 4-21 Percent of Flight Duration Flown at Optimal Flight Level

As illustrated in Figure 4-21, a longer portion of flight duration is on average flown along optimal flight level with increased equipage, while the increase in demand level has the opposite effect. In particular, in the case of mixed operations throughout the track system, the percent of flight time flown along the optimal flight level for 2005 demand level can be improved from 87.0% to 94.1% if the equipage level increases from 0% to 100%; for the 2010 demand level, the corresponding improvement is from 86.3% to 93.4%, and for 2015, from 85.9% to 92.7%.

Similarly, the percent of altitude change requests granted also increases with equipage and decreases with demand (Figure 4-22). As compared to the baseline (0% equipage level), an improvement of about 2.5% can be expected if the equipage increases to 100% in the system with regular tracks and 2005 or 2010 demand levels, and about 4.7% for 2015 demand level; also, an additional improvement of about 1% could be achieved with reduction of lateral separations between tracks to 0.5 degrees.

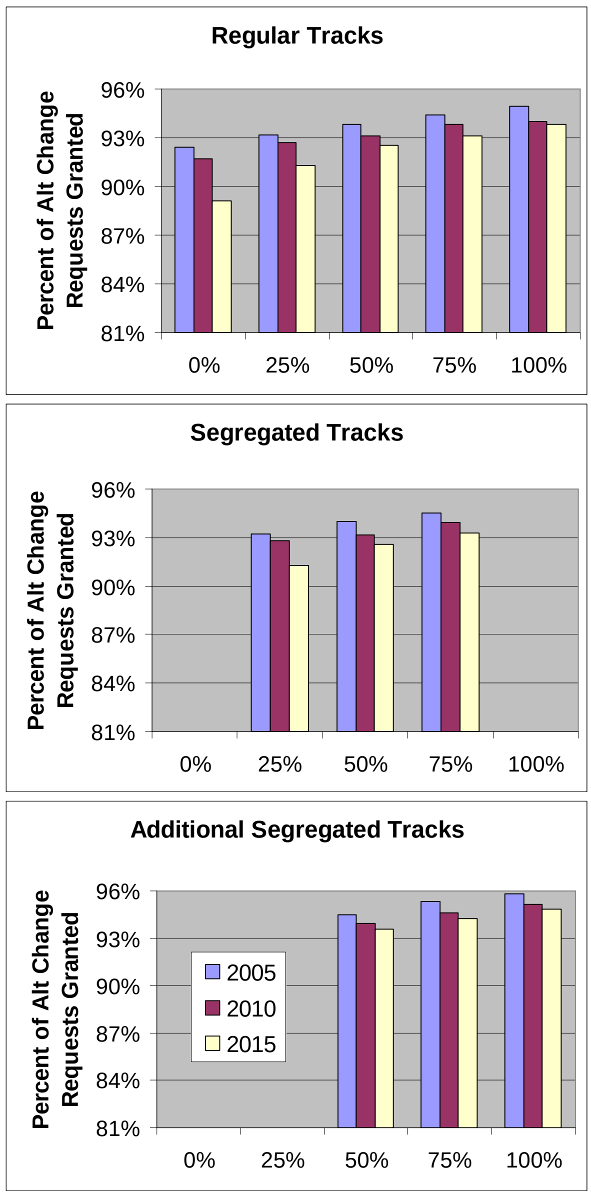

Figure 4-22 Percent of Altitude Change Requests Granted

5 Conclusions

This research effort investigates benefits from reducing the horizontal separations between equipped flights in NAT OTS. It focuses on the sensitivity of benefits to demand and equipage levels, and the effect of procedural rules including the following three cases:

1. Mixed operations of non-equipped and equipped flights throughout the track system (regular track scenarios),
2. Operations of the non-equipped flights prohibited on the reduced-separations tracks (segregated track scenarios), and
3. Lateral separations between the segregated tracks further reduced to allow establishing additional tracks accessible only to equipped flights (additional segregated track scenarios).

Three levels of demand were investigated: traffic demand forecasted for 2005, 2010, and 2015. Traffic forecasts were generated using actual flight schedules realized in 2004 as baseline, and traffic growth parameters published by the ICAO North Atlantic Office. For each of the demand levels, five levels of equipage were investigated: 0, 25, 50, 75 and 100 percent. Reduced separations were assumed applicable only between successive equipped flights; in addition, equipped flights were assumed to plan and perform step climbs within the track system, while non-equipped flights traversed the NAT OTS by maintaining the same flights level assigned to them by the oceanic controlled at the track entry (more precisely, at the corresponding coordinating fix). Benefits figures for each of the investigated scenarios were derived using current procedural and separation standards; in short, these assumed no flight level change while in the track system, and 10 minute separations using MNT (approximately 80 NM).

The main benefits addressed by this research included improvements in operator efficiency through fuel and flight-time savings and additional cargo revenue potential, and improvements in system efficiency through better cruise level assignments (closer to optimal flight level).

Table 5-1 Overall Annual Benefits Summary:
Maximum Possible Additional Cargo Revenue Assumed

	2005				2010				2015			
	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Regular Tracks	$ 36 M	$ 78 M	$ 113 M	$ 133 M	$ 106 M	$ 162 M	$ 251 M	$ 277 M	$ 213 M	$ 334 M	$ 440 M	$ 512 M
Segregated Tracks	$ 8 M	$ 62 M	$ 91 M		$ 45 M	$ 146 M	$ 205 M		$ 139 M	$ 353 M	$ 413 M	
Additional Seg. Tracks		$ 71 M	$ 105 M	$ 151 M		$ 160 M	$ 233 M	$ 300 M		$ 354 M	$ 459 M	$ 569 M

The results show that benefits can be realized regardless of the procedural rules that control track accessibility based on equipage. As illustrated in Table 5-1, if future cargo demand proves sufficient for operators to replace all possible weight in saved fuel by additional cargo, the overall annual benefits increase with equipage and are the highest for the additional segregated tracks scenario: they are as high as $151M, $300M, and $569M for 2005, 2010, and 2015 demand levels, respectively; this roughly translates into average airframe benefits of $317K, $508K and $799K, respectively.

If, however, operators face absolutely no additional cargo demand in future years of interest, the overall annual benefits would still increase with equipage but be as high as $29M, $53M, and $113M for 2005, 2010, and 2015 demand levels, respectively (Table 5-2); this roughly translates into average airframe benefits of $64K, $92K and $166K, respectively.

Table 5-2 Overall Annual Benefits Summary: No Additional Cargo Revenue

	2005				2010				2015			
	25%	50%	75%	100%	25%	50%	75%	100%	25%	50%	75%	100%
Regular Tracks	$ 7 M	$ 16 M	$ 23 M	$ 27 M	$ 23 M	$ 34 M	$ 47 M	$ 51 M	$ 46 M	$ 72 M	$ 92 M	$ 106 M
Segregated Tracks	$ 2 M	$ 9 M	$ 16 M		$ 12 M	$ 26 M	$ 36 M		$ 32 M	$ 67 M	$ 83 M	
Additional Seg. Tracks		$ 12 M	$ 18 M	$ 29 M		$ 29 M	$ 40 M	$ 53 M		$ 67 M	$ 88 M	$ 113 M

One of the most important conclusions from this research effort is that all flights realize benefits on average regardless of their equipage. Of course, some flights experience penalties; however, the average benefits per flight that benefited were significantly higher than average penalties per flight that was penalized; that was true for all investigated demand and equipage levels. In fact, across all investigated scenarios, the results show that a flight with benefits can save on average from 2 to 8 times more than a flight with penalties loose on average.

Equipped flights, however, materialize more frequent benefits than non-equipped flights: on average, they benefit 2–5 times more frequently and get penalized 30%-70% less frequently. In addition, equipped flights also materialize higher savings than non-equipped flights: on average, they benefit 65%–128% more and get penalized 20%-50% less. As a result, equipped flights save on average 1.5-4.6 times more than non-equipped flights.

This clearly provides some incentive for carriers to equip. Furthermore, as equipage increases, cumulative benefits increase as well although the marginal return on equipage decreases. This conclusion is also valid for demand: as demand increases, marginal return on equipage decreases.

Also, since benefits are driven by spatial and temporal distributions of flights, the ability to realize benefits is driven by the characteristics of flights that are close by each other, i.e., characteristics of clusters of flights. Benefits are, therefore, also likely to be driven by whether all flights within a cluster equip.

It is important to point out that the overall effect of reduced separations is highly sensitive to the method used for selection of tracks that are accessible only to equipped flights: results obtained from the 9 test scenarios assuming different choices for segregated tracks for 25% equipage level demonstrate that the average benefits (per flight, regardless of its equipage) can not only be cut in half, but also be reversed into penalties if segregated tracks were not carefully allocated. Therefore, with the exception of results from scenarios assuming 100% equipage level, benefits presented for segregated and additional segregated track scenarios should be treated as conservative.

Finally, as compared to the baseline, an improvement of about 2.5% in the percentage of altitude change requests granted can be expected if all flights obtain equipage in the system with mixed operations and 2005 or 2010 demand levels, and about 4.7% for 2015 demand level; a further improvement of about 1% could be achieved by establishing additional tracks with lateral separations of 0.5 degrees. Similarly, an improvement of about 7% can be expected in the percentage of flight time flown along optimal flight level in the mixed operations environment (for all demand levels), and additional 0.1%, 0.7% and 1.3% increase for 2005, 2010 and 2015 demand levels, respectively, with additional track capacity improvements through a reduction of lateral separations to 0.5 degrees.